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Spatial Variability of Yield and Nitrogen Indicators—A Crop Rotation Approach

Remigiusz Łukowiak [1,*], Witold Grzebisz [1], Jakub Ceglarek [2], Adam Podolski [1], Cezary Kaźmierowski [2] and Jan Piekarczyk [2]

[1] Department of Agricultural Chemistry and Environmental Biogeochemistry, Poznan University of Life Sciences, Wojska Polskiego 28, 60-637 Poznan, Poland; witold.grzebisz@up.poznan.pl (W.G.); adam.podolski@podolski.pl (A.P.)

[2] Environmental Remote Sensing and Soil Science Research Unit, Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Krygowskiego 10, 61-680 Poznan, Poland; jakub.ceglarek@amu.edu.pl (J.C.); cezark@amu.edu.pl (C.K.); jan.piekarczyk@amu.edu.pl (J.P.)

* Correspondence: remigiusz.lukowiak@up.poznan.pl; Tel.: +48-61-846-6287

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Abstract: The division of an arable field into zones of different productivity requires a reliable, discriminatory tool. This hypothesis was validated by analyzing the spatial variability of yield and N indicators in the crop rotation of winter oilseed rape (WOSR)/winter triticale (WTR) during 2016/2017 and 2017/2018 in a field of 30 ha (Przebędowo, Poland). The direct, measurable variables were: yield, N accumulated in—seeds/grain and crop residues, mineral N in spring, and harvest. The basic N indicators were total N uptake (TN), N-partial factor productivity, and N balance (N_b). The attainable yields of WOSR and WTR were 4.93 and 6.51 t ha^{-1}, and a yield gap of −2.04 and −2.10 t ha^{-1}. The management of 50 kg of the non-used N by crops, i.e. nitrogen gap (NG) could cover 36% and 65% of the yield gap (YG), respectively. The N_b, based on N input ($N_{in} = N_{min} + N_f$) and TN, was the key field indicator, defining both yield and NG. Geostatic parameters, i.e., the nugget to sill ratio, spatial dependence range, and mean correlation distance, were very stable (≤0.2–0.17; 94–100 m; 28 m for WOSR and WTR). The spatial stability of N_b, irrespective of the crop and growing conditions, corroborates its suitability for discriminating high and low-productivity field zones.

Keywords: winter oilseed rape → winter triticale cropping sequence; mineral N; N input; N total uptake; N balance; N gap

1. Introduction

The continuous growth in the human population requires an adequate food supply, whose delivery depends on increased yields of the main crop plants [1–3]. The absolutely basic food production factor is breeding progress, resulting in new, efficient varieties [4,5]. The primary agronomic factor is nitrogen (N); its available amount in the soil/plant system is necessary to exploit the potential of the currently grown variety. The yield trends of main crops during the last century corroborate this conclusion, showing high similarities with trends of N use in agriculture [1,6]. As stressed by numerous authors, the success of the Green Revolution was due to interaction between the yield potential of new varieties and the simultaneous increase in the consumption of N fertilizer, which provided crops with strong protection control against diseases and pathogens [1,3]. The consumption of N will also be the key yield driver of crop plants in the coming decades [7,8]. Due to its very complex impact on crop growth and the development of its yield components, N fertilization requires deep scientific knowledge on the one side and high practical skills by farmers on the other. In spite of considerable progress in understanding the N uptake process and its transformation pathways during the vegetative and reproductive stages of crop plants, N recovery from applied N fertilizer (N_f) is unsatisfactory. As reported by Cassman et al. [9] 20 years ago, the recovery of N from applied fertilizers ranged from between 30 to 50%. The non-consumed part of N_f by the currently grown crop undergoes numerous processes that result in its loss to neighboring ecosystems, including both water and air. During the last decades of the 20th century, the well-recognized threat of environmental pollution from active N, including nitrates, and its gaseous compounds (ammonia, N oxides), triggered a strong response in developed countries. In Europe, the best example is the Nitrate Directive, aimed at limiting N dispersion to the environment [10,11]. The agronomic efforts to take N management in agriculture under control comprise a set of different strategies, in fact, focusing on the increase of nitrogen use efficiency (NUE). This term, in spite of a large information capacity, in reality, refers to the increase in productivity of a unit of N by the currently growing plant [12]. For example, the estimated genetic progress in NUE for wheat during the 25 year period (1985–2010) ranged between 0.30 and 0.37% per annum. This was partly related to the increase in the nitrogen harvest index (NHI), a term describing the relative accumulation of N in seeds/grain to the total N in the aboveground parts of a crop [13]. The Organization of Economic Cooperation and Development (OECD) defines NUE as the ratio between the amount of N removed from the field to its amount applied in fertilizer [10]. The weakness of this definition is the non-defined crop part, which is really removed from the field. For example, in wheat, 70–80% of N is allocated in grain. The remaining part of N is in straw, which can be used as fodder for ruminants or bedding material for farm animals. Straw can also be used as an organic fertilizer and directly incorporated into the soil [14].

The second set of measures to increase NUE focuses on the development of efficient practices of N application. The best example is the concept known as four nutrient stewardship for improved NUE [15]. The four pillars of the concept are: (i) Right Source of nutrients, (ii) Right Rate, (iii) Right Time, and (iv) right place. The third pillar, i.e., the right time of application, concerns the synchronization of the calendar time of a particular nutrient application with its real requirement by the actually grown crop. This point, in production practice, in fact, refers to a great extent to the application of N_f because the in-season supply of N directly impacts the development of yield components. It has been well documented that a shortage of N during the stage of inflorescence development by winter oilseed rape results in a reduction of seed density, consequently leading to a yield decline [16,17]. The requirement of a crop for N at a well-defined stage of its growth defines the N_f rate. The classic example is wheat, in which crude protein content increases in response to the late application of nitrogen fertilizer [18].

The fourth pillar of the four nutrient stewardship concept, i.e., the right place, requires more attention because it is also written down in the agronomic concept, known as site-specific nutrient management (SSNM). In general, this concept addresses differences in yields due to variability in nutrient supply to crops, both between fields or within a given field [19,20]. The main reason for the in-field differences in nutrient supply to the currently grown crop is variability in basic soil properties, consequently resulting in a spatial differentiation in water and nutrient supply to plants during the growing season [21,22]. In rain-fed agriculture, effective crop production, in fact, depends on field zones sensitive to water shortages during the growing season [23]. The shortage of water in soil affects numerous processes responsible for the release of mineral N from its organic pools. Effective N management is a major challenge to farmers due to temporal, spatial, and vertical variability in plant N uptake [23–26]. Nitrate N can be taken up by plants even from a soil depth of 150 cm, as has been recognized for some crops such as oilseed rape or maize [27,28].

It is possible to distinguish three pools of mineral N during the growing season that are responsible for N supply to the currently grown crop [29]. The first one is the indigenous mineral N (N_{min}) content present in the soil before a given crop sowing date or before the regrowth of winter crops that are grown in the temperate regions of the world. The second N_{min} pool is directly related to the amount and type of applied N_f. The agronomic aim of N_f application is to increase the N_{min} pool in field zones poor in this nutrient. A sound N management practice requires data on the current status of the N_{min} content. The amount of N_{min}, usually measured in spring, is highly influenced by the preceding crop [29–31]. The third N pool is its amount released from soil organic pools during the growing season [29,32]. Hence, far, the knowledge of this pool size is a typical *black–box* for both scientists and farmers. Research efforts to determine the size of this pool require the achievement of two objectives, i.e., (i) a reliable estimation of the N quantity released from soil resources, and (ii) the implementation of data obtained into fertilizer recommendations. In spite of hundreds of laboratory tests and models, these efforts have not been satisfactory [27,33]. The best way to overcome this limitation is to divide a field into high- and low-productive zones based on N supply. The main target of the field zonation is to recognize the in-season potential of different field zones to N release. It can be assumed that N release from soil resources and its subsequent supply to the currently grown crop differs between high- (yield gain) and low-yielding field zones (potential yield loss) [19,22].

In fields with a highly variable N_{min} content, both vertical and spatial, the uniform N management (UNM) strategy, which still dominates in crop plant fertilization, leads to the under or over-fertilization of some areas of a field [19,26]. The outcome of this strategy for farmers is a self-created risk, both economic and environmental. Understanding the spatial variability in N_{min} supply from the soil during the growing season to the currently grown crop is a very important step in the development and effective in-season N management strategy.

The objectives of the study were (i) to identify spatial variability in yields of winter oilseed rape (WOSR) and winter triticale (WTR) grown in a crop rotation, (ii) to identify the size of the nitrogen gap (NG), (iii) to select the best set of N indicators, i.e., those with the potential to discriminate N field zones differing in N productivity.

2. Materials and Methods

2.1. Site Description

The experimental object was a field of 30 ha, located near the village of Przebędowo, Poland (52°35′11.2″ N and 17°00′8.7″ E), lying on the 75 m ASL (Figure 1). The field has a flat topography with a relative difference of one m. The soil texture varies from sand to loamy sand in the topsoil and from loamy sand to sandy loam in the subsoil, classified as Albic Luvisol. The content of C_{org} ranged from 0.92 to 2.78% and pH from 5.1 to 7.1. The content of available water ranged from 36.6 to 67.7 mm in the topsoil and from 82.3 to 200 mm in the subsoil. The content of available P, K, and Mg was in ranges suitable for winter oilseed rape production (Table 1).

Figure 1. Location of the study field. (source: https://www.google.pl/maps).

Table 1. Soil properties at the beginning of the winter oilseed rape/winter triticale crop rotation.

Variables	Units	Minimum	Maximum	Mean	SD	CV,%
		Plow layer, 0–30 cm				
C_{org} [1]	%	0.9	2.8	1.4	0.4	31.4
pH, 1 M KCl [2]	-	5.1	7.1	5.9	0.5	8.3
Sand	%	70.0	91.0	81.7	4.4	5.4
silt	%	7.0	26.0	14.6	3.7	25.2
Clay	%	1.0	7.0	3.7	1.5	40.6
Rpaw [3]	mm	36.6	67.7	51.2	5.9	11.5
P [4]	mg kg^{-1}	31.5	672	229	136	59.5
K [4]	mg kg^{-1}	122	445	254	81.8	32.2
Mg [4]	mg kg^{-1}	62.5	278	130	46.9	36.0
Ca [4]	mg kg^{-1}	39.8	1974	490	447	91.3
		Subsoil layer, mean for 30–90 cm				
pH, 1 M KCl [2]	-	4.8	6.9	5.8	0.5	8.3
Sand	%	65.0	94.33	80.4	7.6	9.4
silt	%	3.3	30.3	13.4	5.1	37.6
Clay	%	1.3	14.3	6.2	3.3	52.8
Rpaw [3]	mm	83.20	199.6	142.8	24.9	17.4
P [4]	mg kg^{-1}	0.8	261	52.0	56.1	108
K [4]	mg kg^{-1}	22.0	637	142	99	69.6
Mg [4]	mg kg^{-1}	34.1	679	138	109	78.8
Ca [4]	mg kg^{-1}	15.3	5248	495	844	171

[1] organic C - loss of ignation; [2] 1 M KCl, 1:5 soil solution ratio; [3] Rpaw—retention of plant available water (10–500 kPa) in mm; [4] available nutrients, Mehlich 3 extraction solution [34].

The local climate, classified as intermediate between Atlantic and Continental, is seasonally variable (Table 2). Precipitation during the period extending from January to July amounted to 574 mm in 2017, including 217 mm in July, and to 323 mm in 2018, including 93 mm in July. In May and June 2018, critical months for yield components of triticale development, the amount of rainfall was extremely low, amounting to 59 mm. Air temperatures in both years were higher in comparison to the respective long-term averages.

Table 2. Main characteristics of meteorological conditions during the study on the background of the long-term averages [1].

Growing Season	Consecutive Months during the Growing Season												
	VIII	IX	X	XI	XII	I	II	III	IV	V	VI	VII	Average
						Temperature. °C							
2016/2017	18.2	17.1	8.5	3.1	1.7	−2.2	0.5	6.7	7.7	14.2	18.1	19.4	9.7
2017/2018	19.3	13.7	11.0	5.5	2.9	2.2	−2.6	1.0	13.4	17.9	19.4	20.9	10.4
1961–2009	17.5	13.3	8.6	3.6	0	−1.6	−0.5	2.9	7.9	13.2	16.4	18.1	**8.1**
						Precipitation(mm)							
2016/2017	38.6	7.9	129	58.6	58.4	34.7	38.7	46.5	62.9	65.7	108	217	866
2017/2018	143	62.6	123	64.6	69.9	67.2	10.6	41.7	41.7	10.7	58	92.8	786
1961–2009	66.7	48.8	42.0	45.3	48.4	40.1	32.6	40.1	38.1	56.7	62.7	77.2	**599**

[1] meteorological station at Przebędowo.

2.2. Agronomic Operations

The field studies were based on a two-year cropping sequence: winter oilseed rape (WOSR)/winter triticale (WTR) conducted in two consecutive growing seasons: 2106/2017 and 2017/2018, respectively. Winter barley was a forecrop for WOSR. Standard tillage technology was applied for soil preparation for WOSR. Immediately after winter barley harvest, phosphorus and potassium fertilizers were applied on the entire field, and shallow stubble plowing (10–12 cm) + harrowing was done. Three weeks later, a standard plowing at a depth of 25 cm was carried out with simultaneous soil compaction with a Campbell roller. Seedbed preparation and seeding were conducted immediately after plowing. *Brendy*, a population variety characterized by a high-yielding potential for medium fertile soils, was sown on 22 August 2016. The number of seeds for sowing, based on 1000 seed weight, was adjusted, aimed to reach a plant density of 40–50 plants m^2 after emergence. Plants were harvested at the end of July from an area of 3×1 m^2 at each sampling point when the moisture content of seeds was 8% dry weight.

Field preparation for WTR begun directly after WOSR harvest, comprising a shallow stubble plowing (10–12 cm) + harrowing. A control of the postharvest emerging OSR seeds and weeds was done twice during summer by harrowing. In the middle of September, a standard plowing at a depth of 25 cm was carried out. Seedbed preparation and seeding were conducted two weeks later. The *Rotondo* variety, which is suitable for growing on medium fertile soils, was sown on 28 September 2017. The amount of grain for sowing, based on 1000 seed weight, was adjusted, reaching a plant density of 300–350 plants m^2 after emergence. Plants were harvested at the end of July/beginning of August from an area of 3×1 m^2 at each sampling point when the moisture content of seeds was 15% dry weight. A crop-specific program to control weeds, pests and diseases was conducted in accordance with standard farm practice for each of the tested crops, following integrated pest management (IPM) principles.

2.3. Collection of Study Materials and Chemical Analyses

The coordinates of samples were recorded using a handheld GPS device and then exported to a computer. The coordinates were then converted into a point feature class in ArcGIS Pro and connected with the data describing yield parameters and N indicators. The points, recorded originally in the World Geodetic Survey 1984 (WGS 84) coordinate system were projected onto the Poland CS92 format.

Composite soil samples were collected from each point of the field twice a year: (i) at the beginning of each spring season for winter crops; (ii) and after harvest of oilseed rape and triticale in July/August. The soil was sampled in triplicate from each observation point. Soil samples were taken at three depths: 0.0–0.3 m, 0.3–0.6 m, and 0.6–0.9 m. The total number of soil samples (observations) for WOSR and WTR totally equaled 660 (330 for each crop and 165 for each sampling date). The mineral forms of nitrogen, i.e., N_{min} (NH_4^- and NO_3^-), were determined in "fresh" soil samples within 24 h after sampling. Twenty grams of soil were shaken for 1 h with 100 cm^3 of 0.01 M $CaCl_2$ solution (soil/solution ratio 5:1; m/v). Concentrations of NH_4^- and NO_3^- were determined by the colorimetric method using flow injection analyses (FIAstar5000, FOSS) after filtering through Munktell 3 h filter paper. The method of analysis for NO_3^- concentration consists of two basic steps: a reduction from nitrate to nitrite using a cadmium column and then colorimetric determination of nitrite, based on the Griess–Ilosvay reaction with *N*-(1-naphthyl)ethylene-diamine dichloride as a diazotizing agent. Color measurement was done at a wavelength of 540 nm. To determine NH_4^-, a special FOSS ammonia indicator (a mixture of cresol red, bromocresol purple and bromothymol blue) was applied. The measurement was made at a wavelength of 590 nm. The total soil mineral nitrogen concentration (N_{min}) was the sum of NH_4^- and NO_3^-, expressed in kg N ha^{-1}.

Total N concentrations in plant tissues were measured by harvesting aboveground plant material for each crop at the BBCH 89 growth stage. The harvested plant sample was partitioned into subsamples of seeds/grain and harvest residues (straw + dead leaves + stubble) and dried (65 °C). Nitrogen concentrations were determined using a standard macro-Kjeldahl procedure, with an accuracy of 0.1 mg N. The total N content in plant materials was calculated based on the measured nutrient concentration and mass of each crop component, i.e., grain/seed or straw.

2.4. Calculated Plant and Soil Nitrogen Indices

A. Plant and nutrient indices

1. Total nitrogen	$TN = N_a + N_r$ (kg ha^{-1})	(1)
2. Nitrogen harvest index	$NHI = N_a/TN$ (%)	(2)
3. Unit nitrogen accumulation	$UNA = N_{se}/Y$ (kg N t^{-1} seeds)	(3)
4. Unit nitrogen productivity	$UNP = Y/N_{se}$ (kg seeds kg N_{se})	(4)

B. Soil nitrogen parameters

1. N input	$N_{in} = N_{min} + N_f$ (kg ha^{-1})	(5)
2. Mineral N balance	$N_b = N_{in} - TN$ (kg ha^{-1})	(6)
3. Net N gain	$N_{gain} = N_{minr} - N_b$ (kg ha^{-1})	(7)
4. Total N input	$N_{int} = N_{in} + N_{gain}$ (kg ha^{-1})	(8)
5. Nitrogen input efficiency	$NE_{in} = N_{se}/N_{in} \times 100\%$	(9)
6. Total N input efficiency	$NE_{int} = N_{se}/N_{int} \times 100\%$	(10)

where: Y—seed yield, seed yield, t ha^{-1} or kg ha^{-1}; TN—total N uptake, kg ha^{-1}; N_a, N_r—amount of N in seeds/grain, and harvest residues at BBCH 89, kg ha^{-1}, respectively; N_{min}—the amount of mineral N at the WOSR spring regrowth, kg ha^{-1}; N_{minr}—the amount of mineral N after WOSR harvest, kg ha^{-1}. N_f—N fertilizer rate, kg ha^{-1}; TN—total amount of N in WOSR at harvest.

C. Yield gap, (YG) and nitrogen gap (NG) calculation The following set of equations was applied to calculate both indices:

1. Partial factor productivity of N_{in}	$PFP_{Nin} = Y/N_{in}$ (kg seeds kg^{-1} N_{Nin})	(11)
2. Maximum attainable yield	$Y_{att} = cPFP_{Nin} \cdot N_{in}$ (t, kg ha^{-1})	(12)
3. Yield gap	$YG = Y_{att} - Y$	(13)
4. Nitrogen gap	$NG = YG/cPFP_{Nin}$	(14)

where PFP_{Nin} (kg CUs kg^{-1} N) is the unit nitrogen productivity as a function of total nitrogen input in the system at the onset of spring vegetation (N_{in}) and the actual yield (Y; kg CUs). To delineate the role of PFP_{Nin} on yield, the critical value of PFP_{Nin} was defined. In this study, the critical PFP_{Nin} ($cPFP_{Nin}$) was calculated as the average of the third quartile (Q_3) of PFP_{Nin} values measured for each crop in the studied year. To determine the $cPFP_{Nin}$, the calculated PFP_{Nin} values were ranked in ascending order. The third quartile comprises values above the 75th percentile, i.e., representing 12.5% observations with the highest PFP_{Nin} values. The $cPFP_{Nin}$ is the average of the PFP_{Nin} values lying between the 75th percentile and the highest value of the considered data set.

2.5. Statistical Analyses

Three groups of statistical methods were used to evaluate the parameters of yield and indicators of N management. In the first step, the original data sets were analyzed for parameters of descriptive statistics, including mean, minimum, maximum, standard deviation, and coefficient of variation (CV). The normality of distribution of particular characteristics was evaluated based on the Kolmogorov–Smirnov (K–S) test, the skewness and kurtosis, and coefficient of variation (CV). Pearson's correlation coefficients for the studied yield and N characteristics were calculated to generate the correlation coefficient matrix. The relationships between variables representing soil properties were analyzed by principal component analysis, PCA (StatSoft, Inc., Tulsa, OK, USA, 2013).

The raw and recalculated data were checked for normality, and the logarithmic transformation was applied for attributes that did not have a normal distribution. An experimental semi-variogram of every attribute listed in Tables 5, 6, 9, and 10 was computed using the ArcGIS Pro Geostatistical Analyst module. The semi- to the variograms were calculated according following formula:

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(X_i) - Z(X_i + h)]^2 \quad (15)$$

where h is the lag distance, $N(h)$ is the number of pairs for distance h and X_i and $X_i + h$ relate to the value of the variable at locations separated by the distance h. For each property that had a semi-variogram calculated, a model was fitted. The analyzed properties were not found to be anisotropic; therefore, the computed semi-variograms were omnidirectional. These fitted models were described by three major parameters, the nugget (C_0), the sill ($C + C_0$) and the range A_0. The medium correlation distance (MCD) for each attribute was also calculated, according to the formula:

$$MCD = \frac{3}{8} \frac{C}{C_0 + C} A_0 \quad (16)$$

Classes of spatial dependence for the soil attributes were defined based on the ratio of the nugget to the sill. Values of ratio below 0.25 signify strong spatial dependence; those between 0.25 and 0.75 were considered moderately spatially dependent, while those over 0.75 have weak spatial dependence.

Mapping of the variability of analyzed parameters was performed using kriging interpolation techniques. The parameters of models obtained from the variograms were used with the data. Four types of models were used, Spherical, Exponential, Circular and Gaussian. The prediction errors were estimated based on root mean square error (*RMSE*), medium error (*ME*), average standard error (*ASE*), relative root mean square error (*rRMSE*) and mean square deviance ratio (*MSDR*), calculated according to the formulae:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} [Z(X_i) - \hat{Z}(X_i)]^2} \quad (17)$$

$$ME = \frac{\sum_{i=1}^{n} \{\hat{Z}(X_i) - Z(X_i)\}}{n} \quad (18)$$

$$ASE = \sum_{i=1}^{n} \frac{\hat{\sigma}^2(X_i)}{n} \quad (19)$$

$$rRMSE = \frac{RMSE}{\overline{x}} \quad (20)$$

$$MSDR = \frac{RMSE}{ASE} \quad (21)$$

where n is the number of samples, $Z(X_i)$ are observed values at the location X_i, $\hat{Z}(X_i)$ are values at the same location from prediction, $\hat{\sigma}^2$ is the variance of the prediction and is the mean value of attribute x. Values of these errors were calculated based on the leave one out cross-validation method.

3. Results

3.1. Winter Oilseed Rape—Crop N Indicators

The Kolmogorov-Smirnov (K–S) normality test of yield and crop N indicators did not show the normal distribution of original data. The normality of distribution was also evaluated based on the distance between means and medians and for the range of skewness and kurtosis (Table 3). Kim [35] proposed a z-test for evaluation of the normality of raw data. This test is based on the ratio of the skewness/kurtosis to the standard error of a particular variable. According to Ghasemi and Zahediasl [36], the absolute threshold z-score for the normal distribution for a medium-sized sample ($51 < n < 175$) is ±<2.58. The z-score of 2.58 corresponds to prediction with a significance level (α) of ≤0.05. In the conducted study, for the skewness, this assumption was not fulfilled for N_{minr} and Y_{att} or for the kurtosis for unit nitrogen accumulation (UNA) and unit nitrogen productivity (UNP).

Evaluation of yield and N variables based on the coefficient of variation (CV) was conducted using ranges proposed by Wilding and Drees [37]. According to the proposed ranges, CV < 15% is considered as low; 15% < CV < 35% as moderate, and >35% as high sample distribution. In this study, a low spatial distribution was recorded for Nitrogen Harvest Index (NHI), UNA, UNP, and the maximum attainable yield (Y_{att}). A moderate level of variability was recorded for total nitrogen accumulation by WOSR at harvest (TN). The CV values for three variables, such as oilseed yield (expressed in cereals units, Y-OSR-CUs), nitrogen accumulation in seeds (N_a), and nitrogen accumulation in harvest residues (N_r), were only slightly higher than 35%, creating a borderline group between the moderate and the high class of CV. The highest CV, which exceeded 70%, was obtained for the yield gap (YG). This variable had, however, low skewness and kurtosis, fulfilling the assumption of a z-score of <2.58, in fact, indicating its normal distribution [36].

Table 3. Descriptive statistics of WOSR of yield characteristics and indicators of nitrogen management.

Variables	K–S Test, d	Mean	SD	CV,%	Median	Min	Max	Skewness	Kurtosis
Y-OSR-CUs, t ha^{-1}	0.092	6.909	2.452	35.5	6.946	2.734	13.836	0.53	0.12
N_a, kg ha^{-1}	0.091	127.9	45.9	35.9	124.1	55.1	277.9	0.76	0.92
N_r, kg ha^{-1}	0.092	105.2	37.9	36.0	101.1	44.3	233.6	0.99	1.63
TN, kg ha^{-1}	0.070	233.1	81.3	34.9	221.8	99.3	473.0	0.80	0.89
NHI,%	0.054	54.8	4.1	7.5	54.8	42.9	62.5	−0.22	0.14
UNA, kg N_a t^{-1} seeds	0.107	18.7	2.2	11.8	18.7	13.5	27.5	0.82	3.99
UNP, kg seeds kg^{-1} N_a	0.099	54.3	6.4	11.8	53.4	36.4	74.3	0.59	1.99
PFP_{Nin}, kg seeds kg^{-1} N_{in}	0.097	26.5	10.8	40.7	24.8	10.1	55.5	0.80	0.21
Y_{att}, t ha^{-1}	0.143	10.993	1.391	12.7	10.746	8.991	14.745	0.85	0.38
YG, t ha^{-1}	0.076	−4.084	3.030	−74.2	−4.416	−9.595	3.163	0.47	−0.24

Yield in cereals units; N_{in}—nitrogen input; N_a—N accumulated in seeds; N_r—N accumulated in harvest residues; TN—total N uptake by WOSR at harvest; NHI—nitrogen harvest index; UNA—Unit N accumulation; UNP—unit N productivity; PFP_{Nin}—unit productivity of N_{in}; Y_{att}—maximum attainable WOSR yield; YG—yield gap; K–S—Kolmogorov–Smirnov test.

In order to evaluate the relationships between the yield and crop N indicators, a principal component analysis (PCA) was applied. Three PCs with an eigenvalue above 0.70 ($R^2 > 0.50$) explained 91.7% of total variance. The first principal component (PC1) had the largest variance (55.6%) and significant loadings with six of ten variables. The highest loading was exerted by yield (Table A1). PC2 was associated with indicators of N productivity, i.e., UNA, which was positively, and UNP negatively correlated. PC3 had the highest loadings with NHI. The eigenvectors for the examined variables were broadly scattered on the first two PC axes (Figure 2a). The closest to the absolute of 1 was Y-OSR-CUs, followed by a set of direct, measurable variables, such as N_a, N_r, and TN. These three variables, being significantly correlated to each other, exerted the strongest impact on yield (Table S1). The key crop parameters of N productivity, such as partial factor productivity of N input (PFP_{Nin}) and YG, showed significant relationships with the direct, measurable variables (Table S1). They exerted the strongest and at the same time positive impact on Y (r = 0.86 and 0.81, respectively).

3.2. Winter Oilseed Rape—Soil N Indicators

Soil N indicators, evaluated on the basis of the K–S test, analogically as in the case of yield and crop N indicators, were not normally distributed (Table 4). The threshold z-core of ±<2.58 with respect to the skewness was fulfilled for Y-OSR-CUs, N_{min}, N_{in}, efficiency of total N input (NE_{int}), and NG. For kurtosis, this assumption was fulfilled for all variables, indicating a normal distribution [36]. The lowest spatial variability, as results from the analysis of CV, was found for N_{in} and NE_{int}. The significantly lower CV for N_{in} as compared to N_{min} was due to the application of 162 kg ha^{-1} of N fertilizer. The highest variability, exceeding 100%, was found for two N indicators, i.e., N balance (N_b) and N mineralized during the growing season (N_{gain}) (289% and 195%, respectively). The first one, i.e., N_b, ranged from −235 to +178 kg ha^{-1} of N.

The application of PCA showed that three PCs explained 98.2% of the total variance (Table A2). PC1, explaining 65.2% of the total variance, was associated with six of nine variables, from which N_b had a positive loading. The eigenvector for N_b was equal to the absolute of 1. However, it showed the opposite direction to the other five variables with negative loadings (Y-OSR-CUs, N_{gain}, total N input (N_{int}), efficiency of N input (NE_{in}), and NG (Figure 2b). As shown in Table S2, N_b was significantly but negatively correlated with this set of variables. The highest correlation coefficient was recorded for NE_{in} ($r = -0.99$). PC2, accounting for 21.7% of the total variance, was negatively associated with N_{minr} and positively with NE_{int}. Both variables showed an opposite direction on the PC2 axis. PC3, accounting for 11.3% of the total variance, was associated with N_{in}, but it was not significantly correlated with yield.

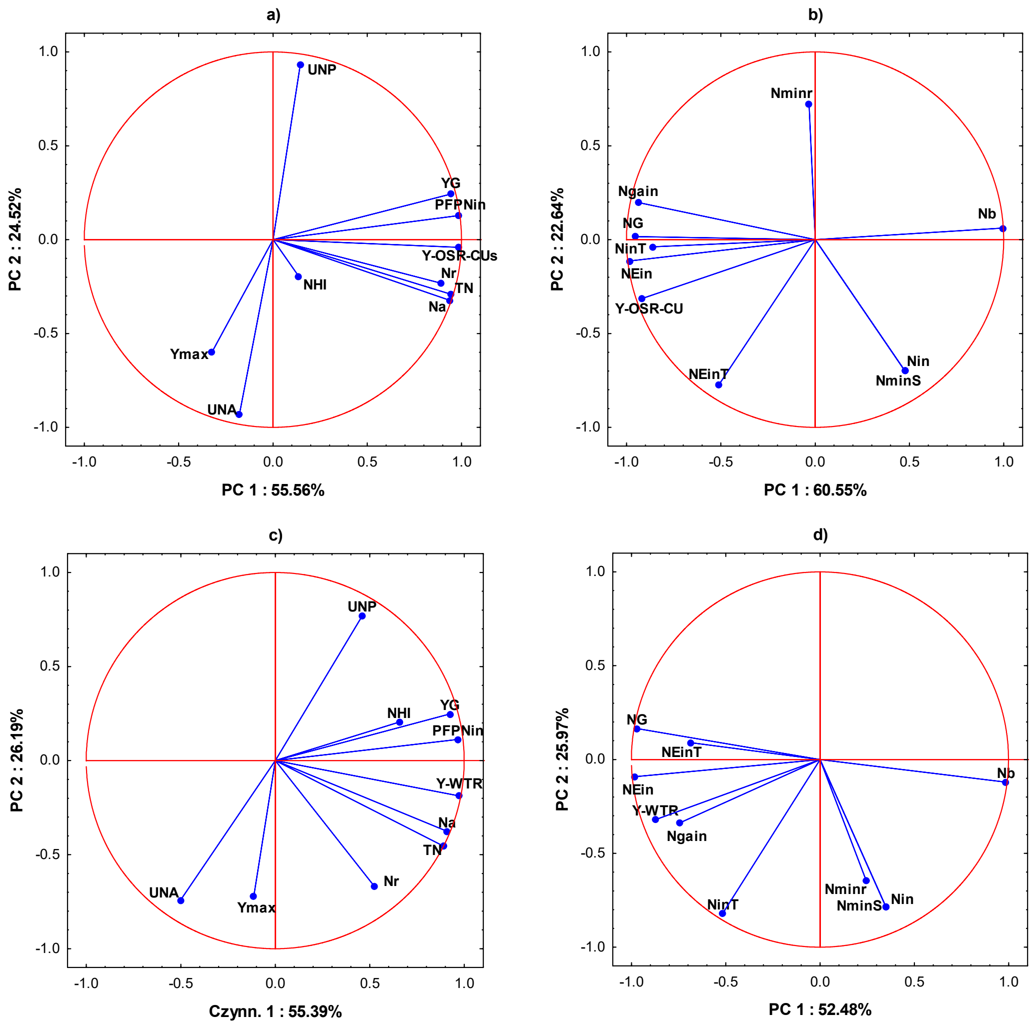


Figure 2. Score plot of yield parameters and nitrogen indices in first principal component (PC1) and second principal component (PC2) axes, (**a**) winter oilseed rape (WOSR)—crop N indicators, (**b**) WOSR—soil N indicators; (**c**) winter triticale (WTR)—crop N indicators; (**d**) WTR—soil N indicators. **Yield parameters and crop indicators**: Yield in cereals units; N_a—N accumulated in seeds/grain; N_r—N accumulated in harvest residues; TN—total N uptake by WOSR/WTR at harvest; NHI—nitrogen harvest index; UNA—unit N accumulation; UNP—unit N productivity; PFP_{Nin}—unit productivity of N_{in}; Y_{max}—maximum attainable WOSR yield; YG—yield gap. **Soil N indicators**: N_{min}—mineral N in spring; N_{in}—nitrogen input (N_{min} + N_f = N fertilizer); N_{minr}—residual N, i.e. N_{min}—measured after harvest; N_b—N balance; N_{gain}—N mineralized during the growing season; N_{inT}—N input total (N_{in} + N_{gain}); NE_{in}—efficiency of N_{in}; NE_{inT}—efficiency of N_{inT}; NG—nitrogen gap.

Table 4. Descriptive statistics of WOSR of soil characteristics and indicators of nitrogen management.

Variables	K–S Test, d	Mean	SD	CV,%	Median	Min	Max	Skewness	Kurtosis
N_{min}, kg ha^{-1}	0.126	102.0	31.7	31.1	98.3	49.1	181.7	0.66	0.12
N_{in}, kg ha^{-1}	0.126	264.0	31.7	12.0	260.3	211.1	343.7	0.66	0.20
N_{minr}, kg ha^{-1}	0.112	79.8	33.8	42.3	74.6	32.9	173.1	1.06	0.77
N_b, kg ha^{-1}	0.133	30.8	89.1	289.1	41.2	−235.2	178.4	−0.89	0.76
N_{gain}, kg ha^{-1}	0.114	49.0	95.5	195.0	34.9	−121.8	331.9	0.85	0.62
N_{int}, kg ha^{-1}	0.118	313.0	86.3	27.6	296.2	169.6	554.1	0.89	0.68
NE_{in},%	0.153	89.8	35.0	39.0	83.5	38.8	205.8	1.12	1.39
NE_{inT},%	0.152	73.6	10.8	14.6	76.9	44.7	88.4	−0.65	−0.27
NG, kg ha^{-1}	0.76	−102.0	75.7	−74.2	−110.3	−239.6	79.0	0.47	−0.24

N_{min}—mineral N in spring; N_{in}—nitrogen input (N_{min} + N_f = N fertilizer); N_{minr}—residual N_{min}—measured after WOSR harvest; N_b—N balance; N_{gain}—N mineralized during. The growing season; N_{inT}—N input total (N_{in} + N_{gain}); NE_{in}—efficiency of N_{in}; NE_{int}—efficiency of N_{int}; NG—nitrogen gap; K–S—Kolmogorov–Smirnov test.

3.3. Spatial Distribution of Yield and N Management Indicators

The studied variables, as shown in Table 5, best fitted four types of semi-variogram models. The spherical model best described the spatial correlation structure of YG, N_a, TN, NG, but the circular one of NHI. The Gaussian model, as reflecting Y-OSR-CUs, and N_b indicates regular and smooth changes in the spatial structure of both variables. In contrast, the exponential model, as achieved for PFP_{Nin} and N_{in}, indicates the irregular, i.e., patchy distribution of both variables [38]. The scale of spatial dependence degree (SDD) was evaluated based on the ratio of structural variance, i.e., nugget (C_0), over the total variance (C_0 + C). Based on Cambardella et al. [39], two classes of spatial dependence for the variables shown in Table 5 were distinguished. A strong SDD, i.e., below 0.25, was found for NHI, N_b, and N_{in}. The latter two variables, representing output and input of N in the balanced equation, respectively, are the key indicators of N management for the cultivated crop in the given growing season [40]. The range of SDD within the studied field was the lowest for N_a (82.3 m), and almost the same was recorded for TN, PFP_{Nin}, and N_{in}. The first three mentioned variables were significantly correlated with Y-OSR-CUs, in spite of a nearly 40-percentage higher SDD (Table S1).

Table 5. Semivariogram parameters of yield and selected plant and soil nitrogen indicators—WOSR.

Variables	Best Fitted Model	Nugget (C_0)	Sill ($C_0 + C_1$)	Parameter Range (A_0, m)	Mean Correlation Distance, MCD, m	Proportion $C_0/(C_0 + C)$	Spatial Dependence
				Yield			
Y-OSR-CUs	Gaussian	0.138	0.147	120.5	2	0.49	Moderate
YG	Spherical	0.084	0.195	159.8	18	0.41	Moderate
				Plant N indicators			
N_a	Spherical	0.086	0.138	82.3	12	0.38	Moderate
TN	Spherical	0.086	0.126	86.3	10	0.41	Moderate
NHI	Circular	0.001	0.006	110.9	34	0.20	Strong
$PFPN_{in}$	Exponential	0.069	0.104	86.3	11	0.40	Moderate
N_b	Gaussian	0.376	1.478	100.3	28	0.20	Strong
				Soil N indicators			
N_{in}	Exponential	0.277	1.085	86.3	24	0.20	Strong
NG	Spherical	0.515	1.168	120.3	25	0.31	Moderate

Y-OSR-CUs—yield of WOSR recalculated in cereals units, t, kg ha^{-1}; YG—yield gap, t, kg ha^{-1}; N_a—N accumulated in seeds, kg ha^{-1}; TN—total N uptake, kg ha^{-1}; NHI—nitrogen harvest index,%; $PFPN_{in}$—partial factor of productivity if N_{in}, kg seeds kg^{-1} of N_{ni}; N_b—N balance, kg ha^{-1}; N_{in}—nitrogen input (N_{min} + N_f = N fertilizer), kg ha^{-1}; NG—nitrogen gap, kg ha^{-1}.

Spatial maps developed for Y-OSR-CUs, N_a, TN, NHI were obtained by ordinary kriging, and for YG, PFP_{Nin}, N_b, N_{in}, NG by simple kriging (Table 6). The cross-validation results of kriged maps for the studied variables were well predicted as indicated for Mean Prediction Error (MPE), which ranged from 0.047 for N_b to −0.070 to TN. The accuracy of prediction was also corroborated by Average Standard Error (ASE) and Root Mean Square Error (RMSE), which were very close to each other, as recorded for most of the studied variables. The prediction error for N_b, as shown by Mean Squared Deviance Ratio (MSDR), was above the threshold value of 1.0 (1.3) [31]. The relative RMSE (rRMSE) for all studied variables was very low, i.e., below the threshold of 25%, clearly corroborating the accuracy of the conducted prediction for all studied variables [41]. The highest rRSME was recorded for Y-OSR-CUs (+14.01%) and the lowest for YG (−1.17%).

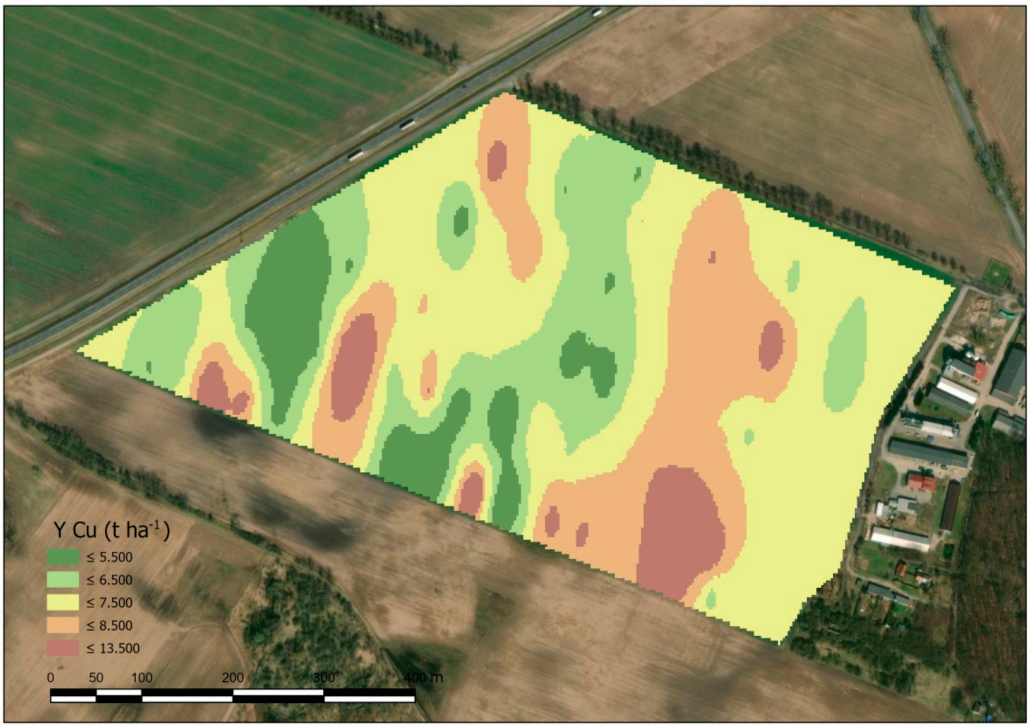
Table 6. Summary statistics of ordinary or simple kriging—WOSR.

Variables	Kriging Type	Mean Prediction Error (MPE)	Root Mean Square Error (RMSE)	Average Standard Error (ASE)	Relative RSME (%)	Mean Squared Deviance Ratio (MSDR)
			Yield			
Y-OSR-CUs	OK	−0.018	2.57	2.96	14.01	0.87
YG	SK	0.017	3.06	3.13	−0.01	0.98
			Plant N indicators			
N_a	OK	−0.046	49.86	52.11	0.85	0.96
TN	OK	−0.070	91.60	93.72	0.51	0.98
NHI	OK	0.004	4.00	3.83	1.87	1.04
$PFPN_{in}$	SK	0.014	10.95	11.55	3.77	0.95
N_b	SK	0.047	112.52	86.61	4.93	1.30
			Soil N indicators			
N_{in}	SK	−0.025	31.84	32.07	0.38	0.00
NG	SK	0.019	78.42	77.09	−1.17	1.02

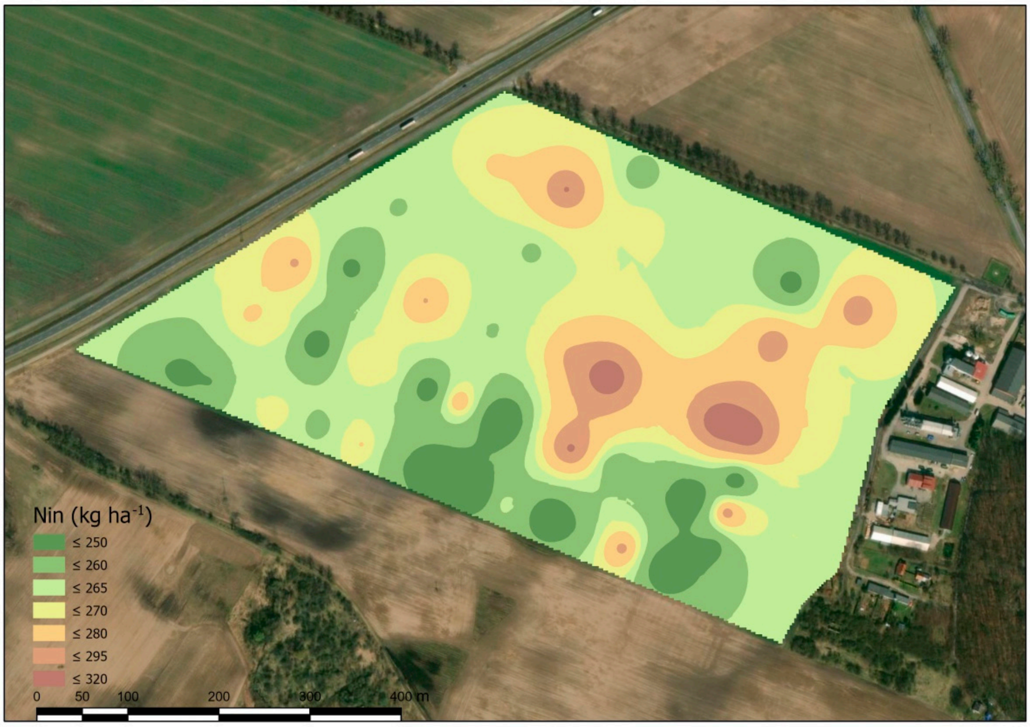
OK—ordinary kriging; SK—Simple kriging; Y-OSR-CUs—yield of WOSR recalculated in cereals units, t, kg ha^{-1}; YG—yield gap, t, kg ha^{-1}; N_a—N accumulated in seeds, kg ha^{-1}; TN—total N uptake, kg ha^{-1}; NHI—nitrogen harvest index,%; $PFPN_{in}$—partial factor of productivity of N_{in}, kg seeds kg^{-1} of N_{ni}; N_b—N balance, kg ha^{-1}; N_{in}—nitrogen input (N_{min} + N_f = N fertilizer), kg ha^{-1}; NG—nitrogen gap, kg ha^{-1}.

Yield, considered as the result of the interaction of numerous growth factors, should reflect both the N supply, i.e., N_{in} and its use efficiency, as measured by the amount of N accumulated in the final yield expressed as TN [29]. The spatial distribution of yield was significantly affected by natural soil factors, as indicated by the high nugget because the sill was at almost the same value (Table 5). The relationship between these two semi-variogram parameters of 1.0 indicates the lack of spatial variability for the WOSR yield [42]. This conclusion, in spite of a spatial range (SDD) of 120 m, is supported by the extremely low MCD (mean correlation distance), which reached 2 m.

The spatial distribution of WOSR-CUs yield showed, in spite of low statistical parameters, a presence of high and low-productive zones, extending in the SE-NW direction of the field (Figure 3a). The lack of spatial yield variability cannot, however, be explained by the impact of intrinsic soil properties because N_{min} did not show a significant relationship with yield. The key reason for the sudden changes between yield zones was the N released during the growing season, as corroborated by a significant correlation of N_{gain} with yield (Table S1). The spatial distribution of N_{in} showed a high heterogeneity within the field. The N_{in} variability was significantly related to N_{min}, which contributed significantly to the total amount of N in the soil/plant system at the onset of WOSR growth. However, this basic N supply indicator was not correlated with yield. In addition, N_{in} showed a patchy distribution on the field area (Figure 3b). The spatial distribution of N_b showed the presence of parallel lying zones with a high and low N balance, extending in the SE-NW direction of the field (Figure 3c). The clearly determined N_b zones can be explained by the nugget to sill ratio, which was 0.2. The high sill can be explained by two factors. The first one was a high amount of N_{min} released from soil resources, indirectly stressing the effect of the intrinsic soil factor on yield [43]. On the other hand, the sill was probably affected by the difference in the sink strength of WOSR distribution within the field [17]. Both factors resulted in a gentle, smooth spatial distribution of N_b, as supported by a reasonably high SDD of 100 m and MCD of 28 m.

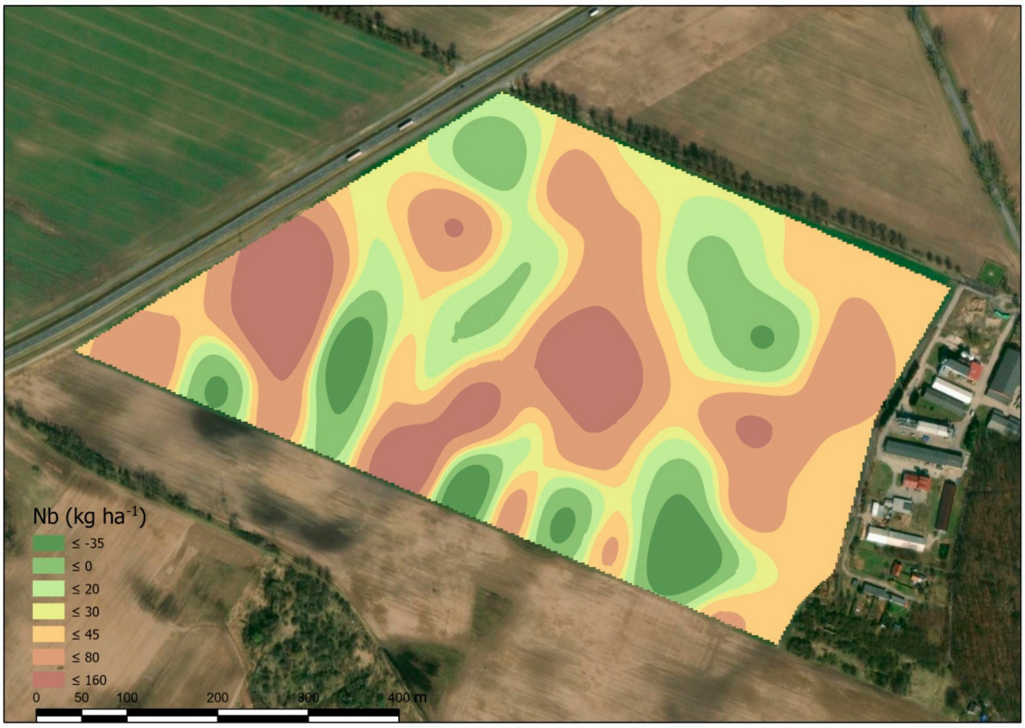


(**a**)



(**b**)

Figure 3. *Cont*.



(**c**)

Figure 3. (**a**) Spatial distribution map of winter oilseed rape (cereals units) yield. (**b**) Spatial distribution map of nitrogen input to winter oilseed rape at the onset of the 2016/2017 growing season. (**c**) Spatial distribution map of nitrogen balance during the winter oilseed rape growing season.

3.4. Winter Triticale—Crop N Indicators

The z-scores for the skewness of all variables fulfilled the absolute threshold of ±<2.58 [36], indicating the normal distribution of original data sets (Table 7). The lowest CV of 6% was recorded for NHI, followed by UNA, UNP (10%). The maximum attainable yield (Y_{att}), in spite of a 5-fold magnitude of PFP_{Nin} variability, showed low spatial variability (13%), ranging from 5.0 to 8.5 t ha^{-1}. The grain yield of triticale of around 5.0 t ha^{-1} ranged over 3.5-fold, i.e., from 2.24 to 8.07 t ha^{-1}. The highest variability of an absolute 79.1% was achieved for yield gap (YG), which ranged from −6.3 to +1.9 t ha^{-1}.

Table 7. Descriptive statistics of triticale yield characteristics and indicators of nitrogen management.

Variables	K–S Test, d	Mean	SD	CV,%	Median	Min	Max	Skewness	Kurtosis
[1] Y-WTR-CUs, t ha^{-1}	0.074	4.991	1.463	29.3	5.167	2.242	8.067	0.29	−0.35
N_a, kg ha^{-1}	0.100	95.5	28.9	30.3	97.3	42.8	160.7	0.32	−0.51
N_r, kg ha^{-1}	0.079	28.0	6.4	22.8	27.2	14.0	40.2	−0.17	−0.60
TN, kg ha^{-1}	0.081	123.5	33.4	27.1	127.3	65.8	199.2	0.21	−0.55
NHI,%	0.093	76.7	4.3	5.6	77.0	65.0	83.4	−0.62	0.04
UNA, kg N_a t^{-1} seeds	0.088	25.0	2.6	10.4	24.9	19.0	31.9	0.28	0.28
UNP, kg seeds kg^{-1} N_a	0.057	40.4	4.2	10.5	40.1	31.4	52.5	0.40	0.57
PFP_{Nin}, kg seeds kg^{-1} N_{in}	0.093	26.9	8.3	30.8	25.7	9.9	49.5	0.64	0.79
Y_{att}, t ha^{-1}	0.137	7.087	0.9	13.4	7.333	4.955	8.571	−0.56	−0.64
YG, t ha^{-1}	0.077	−2.096	1.7	−79.1	−2.145	−6.329	1.916	0.15	0.63

[1] Yield in cereals units; N_{in}—nitrogen input; N_a—N accumulated in seeds; N_r—N accumulated in harvest residues; TN—total N uptake by WOSR at harvest; NHI—nitrogen harvest index; UNA—unit N accumulation; UNP—unit N productivity; PFP_{Nin}—unit productivity of N_{in}; Y_{att}—maximum attainable WOSR yield; YG—yield gap; K–S—Kolmogorov–Smirnov test.

For WTR, two PCs explained 81.6% of the total variance variability (Table A3). PC1 was associated with five of 10 variables, and all had positive loadings. These variables were significantly correlated with each other and with yield (Table S3). The highest score of 0.97 was obtained for Y-WTR and PFP_{Nin}. The eigenvectors of these two variables on the PC1 axis were the same, but they showed the opposite direction on the PC2 axis (Figure 2c). The yield was significantly correlated with N_a and TN (r = 0.95) and PFP_{Nin} with YG (0.98) (Table S3). PC2 explained 26.2% of the total variance and was positively associated with UNP, and as expected negatively, with UNA and with Y_{att}. Both these N indicators were significantly but weakly correlated with both Y-WTR and Y_{att}. NHI, with a score of 0.66, was much closer to PC1 than to PC2. It was significantly, but only moderately, correlated with N_a and Y-WTR, although not with Y_{att} (r = 0.63, 0.58, 0.12, respectively).

3.5. Winter Triticale—Soil N Indicators

The threshold z-score of the absolute <2.58 was exceeded, but only with respect to the skewness, for N_{minr} and NE_{in} (Table 8). A low range of CV was observed only for N_{in}. High variability was noticed for N_b, N_{gain}, and NG. The highest variability of 115%, ranging from −55.6 to 106.4 kg ha^{-1}, was found for N_{gain}. In spite of the high CV, this variable showed an extremely low skewness (0.01) and kurtosis.

Table 8. Descriptive statistics of triticale soil characteristics and indicators of nitrogen management.

Variables	K–S Test, d	Mean	SD	CV.%	Median	Min	Max	Skewness	Kurtosis
N_{min}, kg ha^{-1}	0.137	88.1	25.1	28.5	94.6	31.5	127.5	−0.56	−0.64
N_{in}, kg ha^{-1}	0.137	188.1	25.1	13.4	194.6	131.5	227.5	−0.56	−0.64
N_{minr}, kg ha^{-1}	0.125	99.2	27.8	28.0	100.2	46.8	184.0	0.76	1.19
N_b, kg ha^{-1}	0.118	64.7	36.9	57.1	67.9	−25.9	161.7	−0.21	0.81
N_{gain}, kg ha^{-1}	0.086	34.5	39.7	114.9	33.0	−55.6	106.4	0.01	−0.28
N_{int}, kg ha^{-1}	0.074	222.6	40.4	18.2	224.3	139.3	315.7	0.06	−0.03
NE_{in},%	0.129	66.2	18.2	27.6	64.8	28.9	116.0	0.73	0.87
NE_{int},%	0.086	55.2	10.0	18.2	55.6	34.5	74.8	−0.10	−0.76
NG, kg ha^{-1}	0.077	−55.6	44.0	−79.1	−56.9	−168.0	50.9	0.15	0.63

N_{min}—mineral N in spring; N_{in}—nitrogen input (N_{min} + N_f = N fertilizer); N_{minr}—residual N_{min}—measured after WOSR harvest; N_b—N balance; N_{gain}—N mineralized during the growing season; N_{int}—N input total (N_{in} + N_{gain}); NE_{in}—efficiency of N_{in}; NE_{int}—efficiency of N_{int}; NG—nitrogen gap; K–S—Kolmogorov–Smirnov test.

For soil N indicators, three PCs explained 98.7% of the total variance (Table A4). PC1 accounted for 52.5% of the total variance and had positive loadings with N_b and negative with Y-WTR, N_{gain}, NE_{in}, and NG. The variance explained by PC2 was 26% and had negative loadings for N_{minr} and N_{int}. PC3 accounted for 20.3% of the total variance and was positively associated with N_{in}. The eigenvectors for Y-WTR and NE_{in} were close to the absolute of 1.0 on the PC1 axis, being significantly correlated with each other (Figure 2d; Table S4). On the opposite direction on the PC1 axis was N_b, which was negatively correlated with Y-WTR (r = −0.79), but extremely strongly with NE_{int} (r = −0.96) and NG (r = −0.96) (Table S4, Figure 2d). Yield showed the highest positive relationship with NE_{in} (r = 0.89), followed by NE_{inT} (r = 0.79). Two directly measured variables, i.e., N_{in} and N_{minr} did not show any significant relationship with Y-WTR.

3.6. Spatial Distribution of Yield and N Management Indicators—WTR

In general, spatial variability of yield and N management indicators for WTR was less differentiated as compared to WOSR (Tables 5 and 9). The spherical model of the semi-variogram fitted best to the spatial distribution of three variables, YG, N_b, and N_{in}, and the exponential to the other variables. For both crops in the studied crop rotation (WOSR/WTR), the spherical model was found to be typical for YG and exponential for PFP_{Nin}. The first one indicates smooth changes in the YG spatial distribution (A_0). In contrast, the exponential model suggests a patchy distribution of this particular variable, as corroborated by the highest values of spatial dependence (A_0) and Mean Correlation Distance (MCD). The nugget to sill ratio was, in general, narrow. A strong spatial dependence ($A_0 \leq 0.25$) was recorded for YG, NHI, PFP_{Nin}, N_b, and NG. All other presented variables were in the moderate class, but with the exception of TN, the evaluated ratios were close to the threshold of 0.25. The range of A_0 for Y-WTR was at the same level as recorded for WOSR. The MCD for Y-WTR was 11-fold higher as compared to Y-OSR-CUs, and together with the exponential form of semi-variogram, corroborates the patchy distribution of this variable.

Table 9. Semivariogram parameters of yield and selected plant and soil nitrogen indicators—WTR.

Variables	Best Fitted Model	Nugget (C_0)	Sill ($C_0 + C_1$)	Parameter Range, (A_0), m	Mean Correlation Distance (MCD) m	Proportion $C_0/(C_0 + C)$	Spatial Distance (A_0)
				Yield			
[1]Y-WTR-CUs	Exponential	0.061	0.120	120.5	22	0.34	Moderate
YG	Spherical	0.358	1.152	101.4	26	0.24	Strong
				Plant Nitrogen Indicators			
N_a	Exponential	0.048	0.129	100.3	24	0.27	Moderate
TN	Exponential	0.062	0.090	134.8	16	0.41	Moderate
NHI	Exponential	0.0003	0.003	86.3	29	0.10	Strong
PFP_{Nin}	Exponential	0.038	0.133	180.5	49	0.22	Strong
N_b	Spherical	0.244	1.153	94.1	28	0.17	Strong
				Soil Nitrogen Indicators			
N_{in}	Spherical	0.515	1.123	98.9	20	0.31	Moderate
NG	Exponential	0.073	1.269	131.0	46	0.05	Strong

[1]Y-WTR—yield of triticale, t, kg ha^{-1}; YG—yield gap, t, kg ha^{-1}; N_a—N accumulated in seeds, kg ha^{-1}; TN—total N uptake, kg ha^{-1}; NHI—nitrogen harvest index,%; PFP_{Nin}—partial factor of productivity of N_{in}, kg seeds kg^{-1} of N_{ni}; N_b—N balance, kg ha^{-1}; N_{in}—nitrogen input (N_{min} + N_f = N fertilizer), kg ha^{-1}; NG—nitrogen gap, kg ha^{-1}.

Spatial distribution maps for Y-WTR, N_a, TN, NHI, and PFP_{Nin} were obtained by ordinary kriging, and for YG, N_b, N_{in}, NG by simple kriging (Table 10). The cross-validation results of kriged maps for the studied variables showed a much better prediction as compared to WOSR. The MPE ranged from 0.010 for NG to −0.041 to N_{in}. The high accuracy of prediction was corroborated by ASE and RMSE. The accuracy of prediction was confirmed by MSDR, which for most variables was close to 1.0. The relative RMSE for all studied variables was below 25%, clearly corroborating the accuracy of the predicted results. As in the case of WOSR, the highest value was for yield (+18.21%) and the lowest for YG (−1.75%).

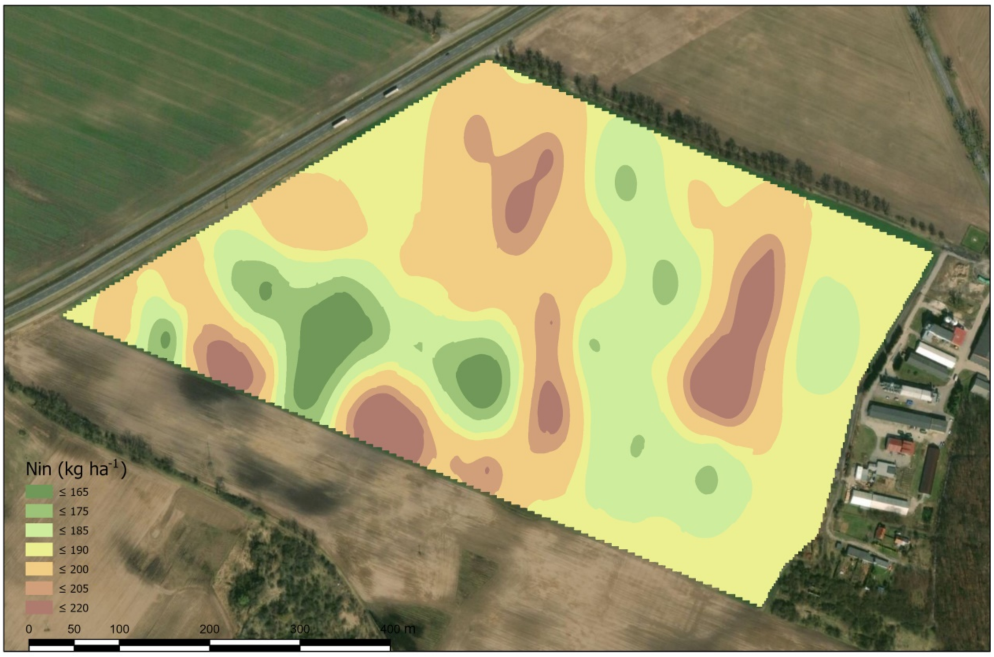
Table 10. Summary statistics of ordinary or simple kriging—WTR.

Variables	Kriging Type	Mean Prediction Error (MPE)	Root Mean Square Error (RSME)	Average Standard Error (ASE)	Relative RSME (%)	Mean Squared Deviance Ratio (MSDR)
			Yield			
Y-WTR	OK	−0.014	1.41	1.60	18.21	0.88
YG	SK	0.005	1.59	1.67	−0.05	0.95
			Plant nitrogen indicators			
Na	OK	−0.003	28.59	32.66	0.87	0.88
TN	OK	−0.007	32.26	34.51	0.68	0.94
NHI	OK	−0.027	4.93	4.21	1.32	1.17
$PFPN_{in}$	OK	−0.016	8.12	8.31	3.35	0.98
N_b	SK	−0.015	35.77	37.63	1.46	0.95
			Soil nitrogen indicators			
N_{in}	SK	−0.041	23.27	25.99	0.48	0.90
NG	SK	0.010	42.27	44.27	−1.75	0.95

OK—ordinary kriging; SK—simple kriging; Y-WTR—yield of triticale, t, kg ha^{-1}; YG—yield gap, t, kg ha^{-1}; N_a—N accumulated in seeds, kg ha^{-1}; TN—total N uptake, kg ha^{-1}; NHI—nitrogen harvest index,%; $PFPN_{in}$—partial factor of productivity of N_{in}, kg seeds kg^{-1} of N_{ni}; N_b—N balance, kg ha^{-1}; N_{in}—nitrogen input (N_{min} + N_f = N fe rtilizer), kg ha^{-1}; NG—nitrogen gap, kg ha^{-1}.

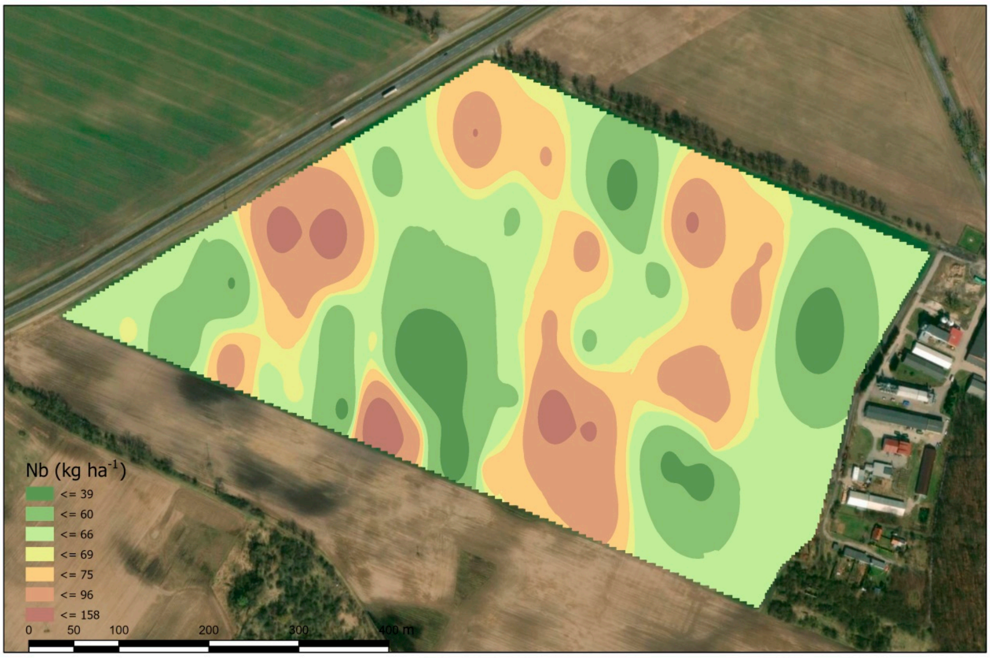
The spatial distribution of WTR yield showed the presence of distinct production zones, extending in an S–N direction in the east part of the field and to the SE–NW in the west part of the field (Figure 4a). The nugget to sill ratio of 0.34 indicates a moderate variability in the spatial distance, which was fully corroborated by the extensive areas of high and low productive zones lying next to each other. However, yield variability, as in the case of WOSR, was weakly related to the key intrinsic soil variable, i.e., N_{min}. Yield showed a significant response to N_{gain}, but not as strong as in the case of WOSR (Tables S2 and S4). The spatial distribution of N_{in}, a variable related to the size of the N_{min} pool at the onset of spring WTR growth, did not show large spatial changes in the studied field (Tables 9 and 10). In the entire field, two low N_{in} zones can be distinguished (Figure 4b). The first one, localized in the west-central part of the field, extended from SE to NW, and the second one, localized in the west part of the field, extended from east to west. The second variable of the N input–output equation, i.e., N_b showed a high nugget to sill ratio, indicating a strong spatial dependence. The spatial distribution of N_b shows a gentle structure in changes of the high and low exploited N zones (Figure 4c).

(**a**)



(**b**)

Figure 4. *Cont.*



(**c**)

Figure 4. (**a**) Spatial distribution map of winter triticale (cereals units) yield. (**b**) Spatial distribution map of nitrogen input to winter triticale at the onset of the 2017/2018 growing season. (**c**) Spatial distribution map of nitrogen balance during the winter triticale growing season.

4. Discussion

The spatial variability of N management in winter oilseed rape (WOSR)/winter triticale (WTR) crop rotation was evaluated based on crop yield parameters and plant and soil indicators of N management.

4.1. Yield—A Diagnostic Based on Crop Nitrogen Indicators

The yield of WOSR and WTR grown in the WOSR/WTR crop rotation, based on principal component analysis (PCA), was a variable with the highest factor loading for PC1. The dominance of yield corroborates the well-recognized fact that the yield of a currently grown crop is the final result of the interactional effect of three main growth factors, i.e., weather conditions during the growing season, soil conditions, and N management [27,43,44]. All yield parameters for WOSR were much higher compared to WTR. The mean yield of WOSR, expressed in cereal units (CUs), was higher by 38% in comparison to WTR. The difference in the maximum attainable yield (Y_{att}) for both crops was even higher, reaching 55%. The yield gap (YG) for WOSR was almost 2-fold wider compared to WTR. The main reason for these large differences was the completely different course of weather in consecutive growing seasons. In 2016/2017, water supply to plants, resulting from the total amount and in-season distribution of precipitation was optimal (Table 1). According to Berry and Spink [45], 300 mm of precipitation in the period, extending from the onset of flowering to the physiological maturity of WOSR, is a prerequisite of a high yield. This condition was fulfilled for WOSR, and this crop yielded at a high level. An optimal supply of water is necessary for reaching the full expression of yield components, decisive for the final yield, such as the number of seeds per unit area (seed density, SD), and seed weight (thousand seed weight, TSW) [17,44,46,47]. The full expression of basic yield components, as affected by favorable weather conditions, in fact, depends on the supply of N during the post-flowering WOSR growth [16]. In contrast to WOSR, the growth of WTR in the 2017/2018 growing season underwent under quite different weather. The total sum of precipitation in May and June, i.e., during the critical months for the development of yield components, amounted to only 59 mm (Table 1).

The growth conditions of both crops can be evaluated on the basis of three crop N indices; the nitrogen harvest index (NHI), unit nitrogen accumulation (UNA) and unit nitrogen productivity (UNP). These indices, parametrizing the utilization efficiency (NUtE) of the supplied N, showed low spatial variability (coefficient of variation, CV < 15%). The extremely low CV for NHI indicates that N partitioning between seeds/grain and the vegetative parts of WOSR and WTR, irrespective of the course of weather during the period extending from the onset of flowering and maturity, was almost the same for the entire field. The conservative trait of the NHI indirectly indicates the occurrence of significant spatial differences in N amount accumulated by both crops in the period just before the onset flowering. It indirectly stresses differences in the spatial distribution of the sink strength, i.e., seed/grain density, as a basic component, defining yield [17]. The presented explanation is strengthened by two N efficiency indices, i.e., UNA and UNP. The conservative behavior of these sets of NUtE indices of N management was strongly expressed for WOSR, being, however, weakly correlated with yield. This result corroborates the opinion of Grzebisz et al. [17], who documented for WOSR that a higher N accumulation in seeds resulted in a higher seed density, which consequently leads to higher yield. This hypothesis was supported by the negative relationship of UNA, but a positive one of UNP with both NHI and yield. The lack of significant relationships of NHI, UNA and UNP with WOSR yield stresses a balanced partitioning of N taken up by plants during the growing season between seeds and vegetative plant parts, irrespective of the field zone. The observed net N uptake by both crops, but especially by WOSR from the soil N pool, released during the growing season, indirectly indicates a continuous supply of N to the growing pods and seeds during the post-flowering stages of WOSR growth. The spatial differences in WOSR yield were probably a result of N status during the phase of inflorescence development [48]. The seed density, as defined at the early stages of pod and seed growth, subsequently affects the plant requirement for N [16].

The NHI for WTR, in contrast to WOSR, exerted a strong and positive impact on yield. This means that the higher the N concentration in grain, the higher the obtained yield was. The negative relationship between UNA and WTR yield can be explained by the N dilution effect. The spatial differences in WTR yield were probably defined during the heading phase of plant growth. In contrast to WOSR, N supply to plants was limited due to drought, and as a result, N accumulated in grains underwent dilution. The dilution effect, which was revealed for WTR, indicates the post-flowering phase as crucial for N partitioning between grain and straw [49].

4.2. Nitrogen Gap

The main objective of the study was to determine the amount of N in the soil/plant system, which was or was not transformed during the growing season into yield. In fact, the key question is to define the extent of the nitrogen gap (NG), i.e., the amount of N which was not taken up by the currently grown crop [29]. The evaluation procedure was based on the assumption that the farmer's target is to achieve an attainable yield (Y_{att}) of 87.5% of the maximum yield in the studied field. It is quite clear that Y_{att} under given soil/weather conditions depends on three main factors: (i) supply of water to plants, (ii) supply of N to plants during the critical stages of yield development, (iii) other soil and agronomic factors responsible for the efficiency of water and N [46,50,51]. This assumption is in agreement with the opinion that in rain-fed agriculture, the attainable level of yield gap closing is in the range of 70–85% of the water-limited yield (Y_w), i.e., the maximum yield in the given soil conditions [52,53].

The WOSR attainable yield, recalculated into cereals units (CUs), was 9.858 t ha^{-1}, which is equal to 4.929 t ha^{-1} of seeds (Figure 5). The Y_{att} obtained under a balanced N supply was at the potential level for WOSR in 2017 in Poland. In the studied field, it covered only 1% of the field area (Figure 3a). The average yield of WOSR of 3.455 t ha^{-1} (=6.909 CUs t ha^{-1}) was high, covering 51% of the field area. This value can be treated as a borderline between high and low productive zones. The average harvested yield was 17% higher as compared to the national average (2.95 t ha^{-1}) [54]. The efficient management of 50 kg ha^{-1} of the N present in the soil/WOSR system could have been the result of the increase of Y_{att} by 1.45 t ha^{-1} of CUs (=0.725 t ha^{-1} of WOSR seeds). This value could cover 36% of the total yield gap (YG) of 4.084 t ha^{-1}, and therefore, it can be treated as a challenge for the farm. The excessive frequency of high-yielding spots, as determined by the mean correlation distance (MCD) of 2 m, was the main disadvantage is the reliable determination of high-, and low-production zones. The principal reason for their appearance was the weather, which created very favorable conditions for WOSR growth in the 2016/2017 growing season.

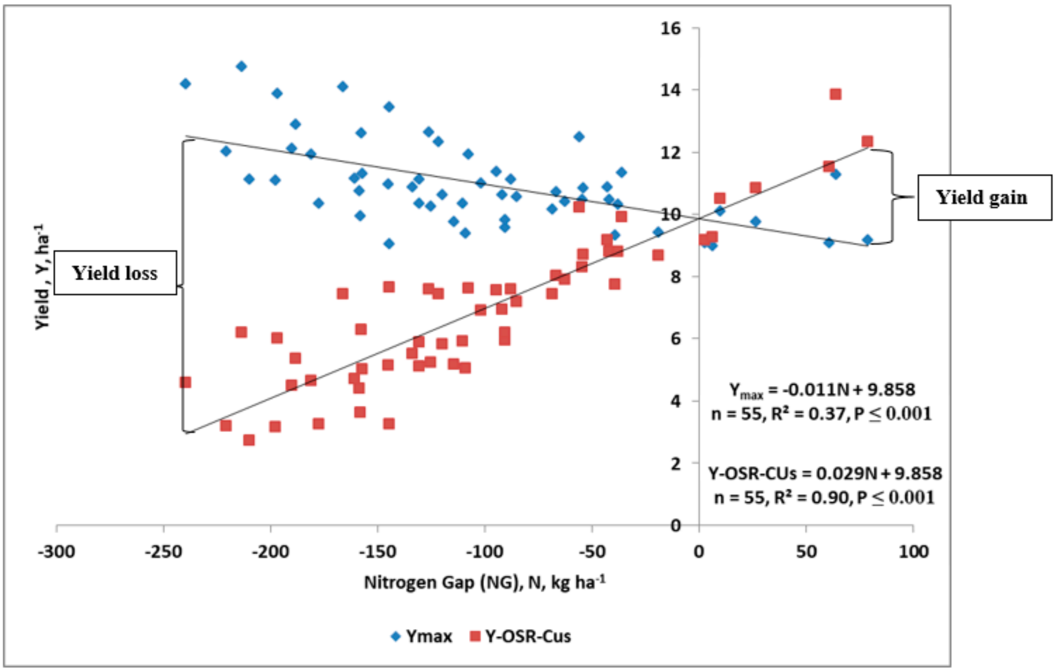


Figure 5. Trends in real and maximum attainable yields in response to nitrogen gap—WOSR. Y-OSR-CUs, Y_{max}—real and maximum attainable yields of WOSR expressed in cereals units.

The average Y_{att} for WTR was 6.514 t ha^{-1}, i.e., it was lower by 34% with respect to Y-OSR-CUs, but higher by 30.5% with respect to the average for the field of 4.991 t ha^{-1} (Figure 6, Table 3). The average WTR yield covered 49% of the total field area. It was by 57.4% higher as compared to the national average (3.17 t ha^{-1}; [55]. The yield gap of 2.096 t ha^{-1} was substantial, constituting 32% of the Y_{att}. The efficient management of 50 kg ha^{-1} of the N present in the soil/WTR system could have been a result of the increase of Y_{att} by 1.37 t ha^{-1}. This value could cover 65% of the total yield gap (YG) of 2.086 t ha^{-1}. The postharvest content of mineral N (N_{min}), i.e., $N_{minr,}$ was by 20 kg ha^{-1} higher in comparison to WOSR (99.2 vs. 79.8 kg ha^{-1}). The production zones of WTR yields, as shown by the exponential model of the semi-variogram, and a high MCD show were theoretically useful tools to distinguish high-, and low-production zones. However, the applicability of the WTR yield map with respect to the one for WOSR was biased by two factors. The first was drought, which significantly affected plant growth during the spring vegetation (Table 2). The exponential model of yield variability could also be a result of excessive soil N mining by WOSR in highly productive zones, as indicated by significant differences in the distribution of N_{in} (Figures 3b and 4b).

The reduction in the N fertilizer (N_f) rate is one of the practical options to decrease the residual N_{min} content after harvest [56]. The simulation conducted for WOSR, assuming both the lower N_f rate of 50 kg ha^{-1}, but the same yield, resulted in a higher NUE, consequently leading to N losses lower by 20% (82 vs. 102 kg ha^{-1}). The strategy of N_f reduction should not, however, be applied to field zones of high N mineralization potential and at the same time of high fertility with respect to the content of available nutrients, responsive to both water and N-use efficiency [26]. Another solution to increase the efficiency of both the indigenous mineral N (N_{min}) but especially N_f is to differentiate the sink strength of plants with respect to the productivity of field zones. It is well recognized that there is a strong dependency between the supply of N and the expression of yield components, as documented for OSR [29,48,57]. This practical solution is based on differentiation in oilseed rape seed density (SD) with respect to the production potential of a particular field zone. As documented by Yang et al. [58], differentiation in SD with respect to the production potential of field zones resulted in an increase of OSR productivity by 32% in low-yielding zones and by 20% in high-yielding zones. This solution clearly indicates that SD should be adjusted to the water and nitrogen capacity of the soil in the respective field zone [1,59,60].

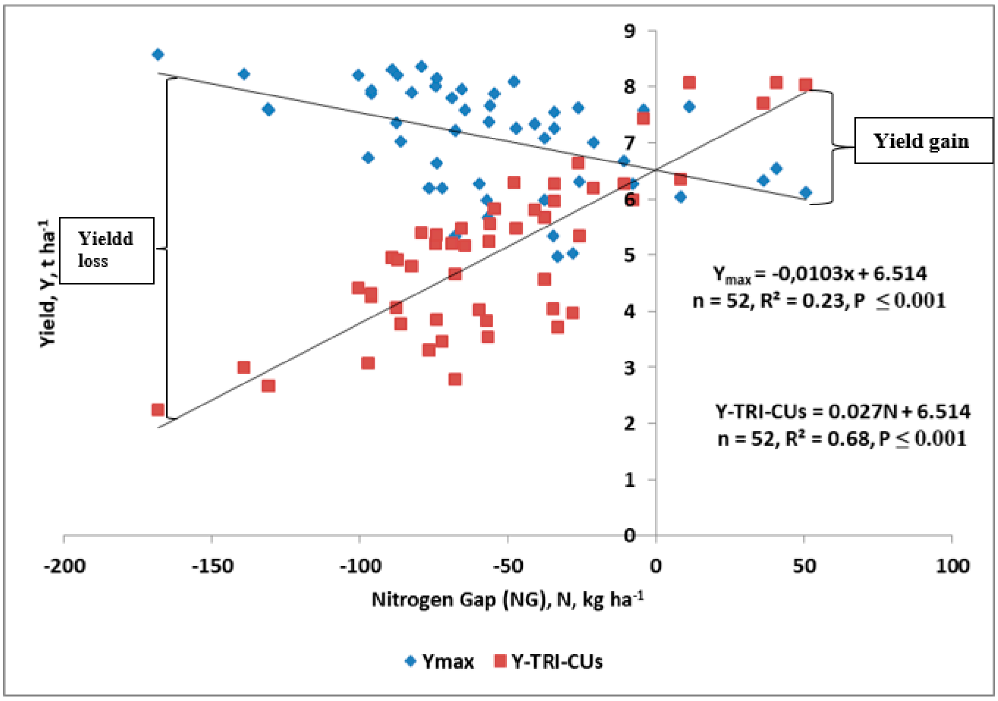


Figure 6. Trends in real and maximum yields in response to nitrogen gap—WTR. Y-TRI-CUs, Y_{max}—real and maximum attainable yields of WTR expressed in cereals units.

4.3. *Yield—A Diagnostic Based on Soil Nitrogen Indicators*

The projected yield of a crop plant, provided there is a good water supply, depends on the amount of available N in the given soil/crop system and its production efficiency [1,11]. In fact, primary sources of N to the currently grown crop are both (i) indigenous N (N_i), i.e., N mineral measured mostly in spring, and (ii) the amount of applied N_f [29]. Spatial variability of N_i should be considered as a core of the implementation of any technology of N management [31]. In spite of available data and knowledge of spatial N_i variability within a field, in practice, a uniform N management (UNM) strategy of N_f application frequently dominates [19,30].

In order to obtain an answer on the worth of the primary N data for yield projection, i.e., referring to the amount of N introduced into the given soil/crop system (N input, N_{in}) and its quantity removed from the system (N output, N_{out} = TN), a N balance (N_b) was applied as a diagnostic tool [16,31]. As shown in Tables S2 and S4, both N_{min} and N_{in} ($N_i + N_f$) were not significantly correlated with the yields of either crop, but significantly with the nitrogen gap. The significant impact of the residual N_{min} on the yield of the succeeding crop was suggested by Baxter et al. [31]. In the studied case, however, no significant relationship was found between WTR yield and N_{min} left by WOSR. On the other hand, the amount of N in seeds/grain and total N uptake showed significant relationships with the yields of both crops (Tables S1 and S3). As a rule of thumb, the lower the N balance (N_b), the higher the expected seed/grain yield may be. The yield of both crops increased in accordance with the decreasing N_b as shown by the developed equations:

1. WOSR: $Y = -0.025N_b + 7.690$ for n = 55, $R^2 = 0.85$, and $p \leq 0.001$ (22)
2. WTR: $Y = -0.031N_b + 7.005$ for n = 52, $R^2 = 0.62$, and $p \leq 0.001$ (23)

The constant of both equations indicates an input/output balance. Therefore, N_b can be used as the key indicator of N management in the given field. It is worth stressing that in spite of the different weather in the studied growing seasons, both threshold values differed by only 10%. For both crops, the highest yields were obtained with the most negative N_b values, indicating the net N gain by plants, i.e., those mining the intrinsic N pool. The higher R^2, as achieved for WOSR, clearly documents that N mining covered a slightly larger area of the field (0.27 ha) as compared to WTR (0.04 ha) (Figure 4c). For triticale, the negative N_b was incidental, without any impact on the dominant trend (Figure 4c). The yield increase, in spite of N_{in} exploitation, was possible due to a net N release during the growing season from N resources (N_{gain}). The relationship between N_b and the amount of N mineralized during the growing season (N_{gain}) showed the same direction as observed for yield:

1. WOSR: $Y_{gain} = -1.003N_b + 79.9$ for n = 55, $R^2 = 0.88$, and $p \leq 0.001$ (24)
2. Triticale: $Y_{gain} = -0.794N_b + 85.9$ for n = 52, $R^2 = 0.55$, and $p \leq 0.001$ (25)

These four equations clearly show that the pool of available N was much better balanced in soil cropped by WOSR than by WTR. One kg of N released from soil resources during the WOSR growing season had the same production value as one kg of N present in the soil/plant system at the onset of spring vegetation. For WTR, its efficiency, as indicated by the direction coefficient of Equation (25), was lower by 20%.

The next aspect of N indicator evaluation is the relationship between N_b and NG. Both N indicators are calculated in different ways. The studied crops showed a quite different impact on the relationship between both N indices. As shown in Figure 7, the negative NG, explicitly indicating the non-exploited N_{min} pool, began at N_b equal to −99.1 kg ha^{-1}. The balanced N_b (0.0) resulted in an NG of −77.8 kg ha^{-1}, indicating a surplus of N_{in}. Triticale showed a significantly different relationship between N_b and YG. As shown in Figure 8, negative NG began at N_b equal to +16.2 kg ha^{-1} of N, clearly indicating a surplus of N_{in} in the soil/crop system. The balanced N_b resulted in a net N_{min} gain of 18.6 kg ha^{-1}. Under favorable weather conditions, as recorded in the 2016/2017 growing season, strong mining of the N_{min} released during the growing season does not mean its full depletion in the high-yielding zones of the field. A high rate of N_{min} release also took place in the low-yielding field zones. In the case of WOSR, the NG pool was dominated by N released during the growing season. Under quite the opposite weather conditions, as recorded in the 2017/2018 growing season, the N_{min} release during the growing season was of secondary importance. The increase in the NG pool was high due to the low exploitation of N present in the crop/soil system at the onset of spring vegetation. The main reason for the increase of this pool was not drought, as suggested in numerous papers [1,32], because N release from soil resources did not stop, as shown in Table 6. The key reason for the low exploitation of N_{in} was a shortage of N supply to plants during the development of yield components, subsequently leading to a decrease of sink capacity. This conclusion is supported by almost a double reduction in total N uptake by WTR as compared to WOSR (Tables 3 and 7).

The relationship obtained in this study is, to some extent, contradictory to the option that assumes an N_f rate reduction, which is suggested as the best management N solution, leading to the decrease in the amount of the residual N in the soil/crop system [10,27]. The dependency obtained indicates this option is suitable for the low-yielding field zones. A productive-oriented strategy should, however, rely on a sink strength increase by the currently cultivated crop [17,58]. Winter oilseed rape is an excellent example of a crop sensitive to this production strategy, provided reasonable high fertility of soil [17]. WOSR production success depends on the ability of the plants to take a set of nutrients during the post-flowering growth, supporting the growth of pods and seeds, consequently increasing the seed density [16,17,48]. The problem of reasonable high soil fertility does not, in fact, refer to the content of P, K or Mg in the topsoil. As it has been recently documented, not only N but also the abovementioned nutrients are taken up from the entire soil profile [24,25,61]. Processes responsible for the N_{min} pool size are quantitatively associated with active pools of other nutrients [24,25]. It can, therefore, be concluded that the determination of effective production zones in a given field cannot be conducted independently of the other nutrients determining N use efficiency.

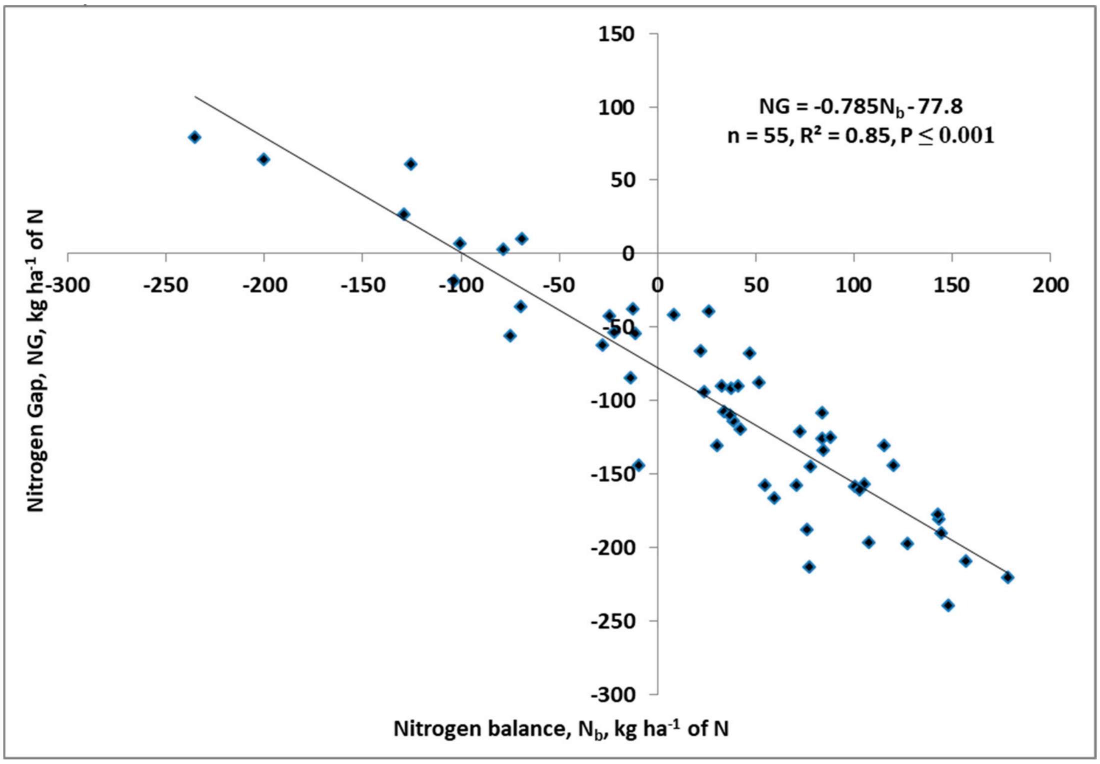


Figure 7. Effect of nitrogen balance in WOSR on the nitrogen gap variability.

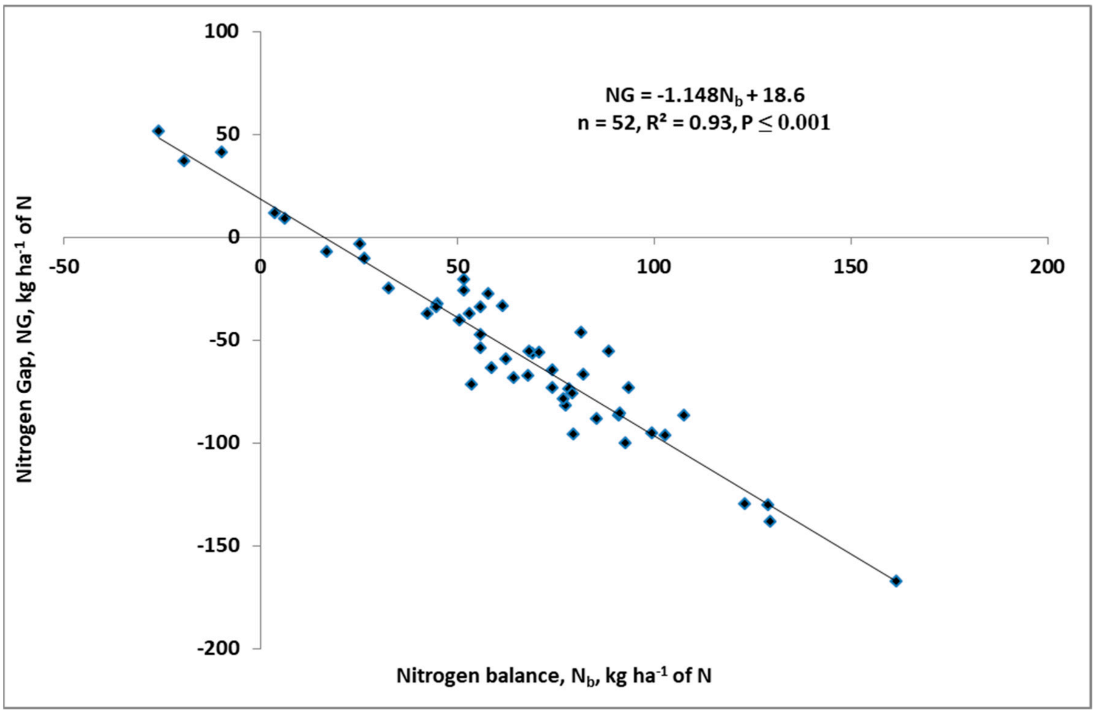


Figure 8. Effect of nitrogen balance in WTR on the nitrogen gap variability.

5. Conclusions

The N balance (N_b), based on N input (N_{min} + N_f) and N output (TN), was the key N indicator, defining both the yield and nitrogen gap of both crops. Its significant impact on these two characteristics was due to the high accuracy of the prediction of low and high-yielding zones. The applicability of N_b as the key N indicator was not defined by the amount of N_{min} in the soil/plant system at the onset of spring vegetation. Neither N_{min} nor N_{in} significantly affected the yield of either crop. The net N_b was deeply related to the amount of N in the crops at harvest, indirectly indicating the importance of the sink strength, i.e., the number of seeds/grain per unit area as the driving factor of yield. The usability of N_b as a tool for determining arable field zones of different productivity was corroborated by PCA, which indicated yield and N_b as dominant loadings in the soil/plant system. The geostatic parameters, such as the nugget to sill ratio, spatial dependence range), and mean correlation distance for N_b were very close or the same (≤0.2–0.17; 94–100 m; 28 m, respectively for WOSR and WTR), clearly indicating both a strong spatial dependence and at the same time the spatial stability of this N indicator, irrespective of the crop and the growing conditions.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/10/12/1959/s1, Table S1. Matrix of Pearson's correlation coefficients between yield and plant indices of N management by WOSR. *n* = 55. Table S2. Matrix of Pearson's correlation coefficients between yield and soil indices of N management by WOSR. *n* = 55. Table S3. Matrix of Pearson's correlation coefficients between yield and plant indices of N management by triticale, *n* = 52. Table S4. Matrix of Pearson's correlation coefficients between yield and soil indices of N management by triticale, *n* = 52.

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Appendix A

Table A1. Pearson's correlation matrix between yield selected plant nitrogen variables and PCA factors for winter oilseed rape, *n* = 55.

Variables	PC1	PC2	PC3
Yield, Y-OSR-CU [1], t ha^{-1}	**0.97** [4]	0.11	0.02
Seed N, N_a, kg ha^{-1}	**0.91**	0.38	0.04
Residual N (N_r), kg ha^{-1}	**0.87**	0.29	−0.38
Total N uptake, TN, kg ha^{-1}	**0.92**	0.35	−0.15
N harvest index,%	0.12	0.20	**0.92**
Unit N accumulation, UNA, kg N_a t^{-1} seeds	−0.28	**0.90**	0.11
Unit N productivity, UNP, kg seeds kg^{-1} N_a	0.28	**−0.90**	−0.08
PFP_{Nin} [2], kg seed kg^{-1} N_{in} [3]	**0.94**	−0.11	0.10
Y attainable, Y_{att}, t ha^{-1}	−0.39	0.56	−0.29
Yield gap, YG, t ha^{-1}	**0.92**	−0.26	0.16

[1] Y-OSR-CUs—yield expressed in cereals units (CUs); [2] PFP_{Nin}—partial factor productivity of N input; [3] N_{in}—N_{min} + N_f in the soil at the WOSR spring regrowth; [4] bold = correlation coefficients for R^2 ≥ 0.50.

Table A2. Pearson's correlation matrix between yield selected soil nitrogen variables and PCA factors for winter oilseed rape, *n* = 55.

Variables	PC1	PC2	PC3
Yield, Y-CU [1], t ha^{-1}	**−0.95**	0.20	0.14
N input at spring, N_{in} kg ha^{-1}	0.40	0.39	**0.83**
Mineral N after harvest, N_{minr}, kg ha^{-1}	−0.01	**−0.96**	0.26
N balance, N_b, kg ha^{-1}	**0.99**	0.01	0.02
In-season mineralized N, N_{gain}, kg ha^{-1};	**−0.93**	−0.35	0.08
Total N input, N_{inT}, kg ha^{-1}	**−0.89**	−0.24	0.39
Efficiency of N input, NE_{in},%	**−0.99**	0.03	0.03
Efficiency of total N input, NE_{inT},%	−0.55	**0.81**	0.04
Nitrogen gap, NG, kg ha^{-1}	**−0.94**	0.05	−0.28

[1] N_{in}—N_{min} + N_f in the soil at the WOSR spring regrowth; bold—correlation coefficients for $R^2 \geq 0.50$.

Table A3. Pearson's correlation matrix between yield selected plant nitrogen variables and PCA factors for winter triticale, *n* = 52.

Variables	PC1	PC2
Yield, Y-CU [1], T ha^{-1}	**0.97** [4]	−0.19
Seed N, N_a, kg ha^{-1}	**0.91**	−0.38
Residual N (N_r), kg ha^{-1}	0.53	−0.67
Total N uptake, TN. kg ha^{-1}	**0.89**	−0.45
N harvest index,%	0.66	0.20
Unit N accumulation, UNA, kg N_a t^{-1} seeds	−0.50	**−0.74**
Unit N productivity, UNP, kg seeds kg^{-1} N_a	0.46	**0.77**
PFP_{Nin} [2], kg seed kg^{-1} N_{in} [3]	**0.97**	0.11
Y attainable, Y_{att}, t ha^{-1}	−0.11	**−0.72**
Yield gap, YG, t ha^{-1}	**0.92**	0.25

[1] Y-cu. yield expressed in cereals units (cus); [2] PFP_{Nin}—partial factor productivity of N input; [3] N_{in}—N_{min} + N_f in the soil at the WOSR spring regrowth; [4] bold = correlation coefficients for $R^2 \geq 0.50$.

Table A4. Pearson's correlation matrix between yield selected soil nitrogen variables and PCA factors for winter triticale, *n* = 52.

Variables	PC1	PC2	PC3
Yield, Y-CU [1], t ha^{-1}	**−0.91**	−0.03	0.37
N input at spring, N_{in} kg ha^{-1}	0.26	−0.31	**0.91**
Mineral N after harvest, N_{minr}, kg ha^{-1}	0.22	**−0.96**	−0.15
N balance, N_b, kg ha^{-1}	**0.97**	−0.09	0.21
In-season mineralized N, N_{gain}, kg ha^{-1}	**−0.75**	−0.59	−0.30
Total N input, N_{inT}, kg ha^{-1}	−0.57	**−0.77**	0.27
Efficiency of N input, NE_{in},%	**−0.99**	0.00	0.02
Efficiency of total N input, NE_{inT},%	**−0.71**	0.53	0.44
Nitrogen gap, NG, kg ha^{-1}	**−0.95**	0.15	−0.20

[1] N_{in}—N_{min} + N_f in the soil at the WOSR spring regrowth; bold—correlation coefficients for $R^2 \geq 0.50$.

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