

Article

Using Remote and Proximal Sensing in Organic Agriculture to Assess Yield and Environmental Performance

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Abstract: Satellite and sensor-based systems of site-specific fertilization have been developed almost exclusively in conventional farming. Agronomic and ecological advantages can also be expected from these digital methods in organic farming. However, it has not yet been investigated whether the algorithms and models are also applicable under organic farming conditions. In this study, the digital data and systems tested in the years 2021 and 2022 in southern Germany were (a) reflectance measurements with a tractor-mounted multispectral sensor, calculation of the vegetation index REIP, and application of algorithms; (b) satellite data in combination with the plant growth model PROMET; and (c) determination of the vegetation index NDVI based on satellite data. They were used to determine plant parameters (crop yield, biomass potential) and to calculate nitrogen balances at a high spatial resolution (10×10 m). The digital systems were tested at two sites with different organic farming systems (arable farming and dairy farming). Validation of the digital methods was carried out with ground-truth data from manual biomass sampling and combine harvester yield measurement. The nitrate leaching risk from the crop rotations of the farms was analyzed via site-specific N balancing using multi-year satellite data. The N balances were validated by measuring nitrate concentrations in leakage water. Additionally, soil properties, such as soil organic carbon (SOC) and total nitrogen (TN), were measured at the sub-field level. Using geostatistics, plant data, soil properties, and nitrate measurements were transferred into grids of the same resolution to enable correlation analyses. The correlations between yield determined with digital systems and the validation data were up to $r = 0.77$. Site-specific N balancing showed moderately positive correlations with nitrate concentrations in leakage water ($r = 0.50$ – 0.66). The strongly positive influence of the soil properties SOC and TN on crop yields underlines the importance of soil organic matter on soil fertility and site-specific yield potentials. The results show that digital methods allow the spatially high-resolution determination of yields and nitrogen balances in organic farming. This can be the basis for new management strategies in organic farming, e.g., the targeted use of limited nutrients to increase yields. Further validations under differentiated soil, climate, and management conditions are required to develop remote and proximal sensing applications in organic farming.



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1. Introduction

Digital technologies in agriculture, such as site-specific fertilization, can help to increase yields and nutrient efficiency, mitigate nitrogen emissions, and thus reduce negative impacts on the environment [1]. The digital systems of precision farming were developed almost exclusively under the conditions and for the application of conventional farming; they have hardly been used in organic farming. However, there may also be an increasing potential for precision farming technologies' application in organic farming [2], especially as the organic cultivation area is growing [3,4], and further growth is expected. The European Green Deal aims to expand organic farming to 25% of agricultural land by 2030 [5].

Proximal and remote sensing systems have predominantly been applied in conventional farming systems. In precision farming, sensor-supported systems are used to apply mineral nitrogen fertilizers site-specifically, taking into account the yield potential and the nitrogen supply of the plants [6,7]. In addition, sensor and satellite data enable the site-specific determination of plant parameters, the analysis of the spatial variability of yields [8,9], and the risk of nitrogen losses via N balancing on the sub-field level [10,11].

Agronomic and environmental benefits can also be expected in organic agriculture from using digital methods. Due to restrictions (no use of mineral fertilizer nitrogen, predominantly organic nitrogen input sources [12,13] with different nitrogen use efficiency compared to mineral nitrogen [12], and area-based animal husbandry) at the farm and field level, the amount of nutrients and their efficiency are a yield-limiting factor in organic farming [14–16], especially in arable farming [17]. While conventional farming systems often have high and environmentally hazardous nutrient surpluses [10], nutrient balances in organic farming are often negative, leading to a decrease in soil nutrient levels and yield potential. Therefore, in organic farming, it is necessary to use the limited organic fertilizers available as efficiently as possible [16]. A better knowledge of the spatial variability of soil properties, soil nutrient contents, and yield potentials on heterogeneous arable land could be the basis of site-specific management decisions in organic farming, e.g., variable rate fertilization of organic fertilizers. However, the question arises whether the algorithms and models calibrated in conventional systems for digitally determining site-specific yields and nitrogen fertilizer requirements can be applied to organic farming systems with significantly lower N fertilization and correspondingly altered vegetation structure and yield formation.

Organic cropping systems have considerably lower yields than conventionally managed systems [18]. An essential strategy in organic farming to increase yields is to enhance soil fertility, nutrient, and humus contents [19] and to improve crop rotations to optimize the N transfer between legumes and non-legumes and the efficiency of applied organic fertilizers [20]. Humus and nutrient management are closely linked in organic farming [21]. In studies on the spatial variability of soil and plant parameters, close relationships were found between organic carbon (SOC) content, total nitrogen (TN) content, and yields on heterogeneous croplands [11,22,23]. These studies were performed with digital methods in conventionally managed agricultural fields. So far, it has not been investigated whether plant parameters and soil properties in organically managed systems have similar or even stronger relationships.

In this study, the application of digital methods to determine plant parameters (crop yield, nitrogen uptake) and calculate nitrogen balances at a high spatial resolution is tested at two sites with different organic farming systems (arable farming, dairy farming). One study site is characterized by medium heterogeneity and the other by high heterogeneity of soil properties and topography. The digital methods used to determine the site-specific yield and N uptake are (a) reflectance measurements with a tractor-mounted multispectral sensor (calculation of the vegetation index REIP and application of algorithms) [8,24], (b) satellite data in combination with the plant growth model PROMET [25], and (c) the determination of the vegetation index NDVI based on satellite data for the estimation of relative biomass potential maps (relBMPmap). Validation of the digital methods is carried out with ground-truth data obtained via manual biomass sampling and yield measurement at the combine harvester. Site-specific nitrogen balances as indicators of N loss risks [26] are calculated based on multi-year satellite data.

To analyze the causes of yield variability, the soil properties SOC, TN, pH, and P were measured and georeferenced, and soil maps were produced. Geostatistical methods were used to transfer the measured data and digital data into grids of equal spatial resolution to examine relationships via correlation analyses.

Based on the current state of knowledge, the following hypotheses were formulated:

1. Sensor- and satellite-based methods for determining site-specific crop yield and nitrogen uptake are applicable for crops in organic farming, particularly winter grains, and provide sufficiently accurate results.

2. Remote sensing allows the calculation of nitrogen balances in organic crop rotations at the sub-field level to assess the risks of nitrogen losses. Calculated site-specific N balances are positively related to measured nitrate concentrations in leakage water from deep drilling.
3. In long-term organically managed arable fields, the soil carbon content is closely related to site-specific yields.

This study aims to provide new scientific insights into the application potential of remote and proximal sensing in organic farming systems to assess their agronomic and environmental performance. The results of the study will be used to assess whether digital systems can support humus and nutrient management in organic farming.

2. Materials and Methods

2.1. Site and Weather Conditions

The investigations were carried out at two experimental sites, (A) Burghausen and (B) Freising, which were chosen because of their different soil and climate conditions as well as different land use over many years (Table 1).

Table 1. Study fields.

Experimental Site	Burgkirchen	Freising	Freising
Field	A1	B1	B2
Region	Burgkirchen	Freising	Freising
Coordinates	80 km east of Munich 48°39'60" N 12°68'14" E	30 km north-east of Munich 48°08'15" N 11°64'33" E	30 km north-east of Munich 48°40'23" N 11°64'64" E
Farm type	Dairy farm (farm A)	Arable farm (farm B)	Arable farm (farm B)
Livestock [LU ha ^{−1}]	1.50	0	0
Size [ha]	4.6	5.2	4.4
Soil type	Cambisol	Haplic Luvisol	Haplic Luvisol
Texture	sandy silty loam – silty loam	sandy loam – loamy clay	loamy sand – loamy clay
Height [m]	452 (448–454)	493 (481–507)	480 (471–491)
Crop rotation	Grass-clover – grass clover – silage corn – winter wheat	Triticale – grass clover – winter wheat – winter rye + catch crop	Winter wheat – grass-clover – winter wheat – winter rye
Grass-clover management	Silage production, 4–5 times cutting, legume proportion 70%	Green manuring, 2–3 times mulching, legume proportion 60%	Green manuring, 2–3 times mulching, legume proportion 60%

2.1.1. Experimental Site A

Experimental site A (Burghausen) is located on the Alzplatte, an area in southern Bavaria (80 km east of Munich) characterized by a smooth, hilly landscape. Washed drift is overlain by two-to six-meter-thick loess-loam blankets with zero to ten percent skeletal proportion (fragments > 3 mm). The soils of this region can be regarded as relatively homogeneous. The investigated arable field of 4.6 ha is a medium-quality Cambisol with an average of 25% clay, 57% silt, and 18% sand (sandy to silty loam, Table 1).

The mean annual precipitation (1996–2022) of site A is 870 mm per year, and the mean annual temperature is 8.9 °C (Table S1). The years 2018 and 2019 were characterized by a warm, dry spring. While cooler temperatures prevailed in May 2019 and more than 150 mm of precipitation fell, the summer months of 2019 remained warmer and dryer than average. The year 2020 was characterized by a dry spring and a wet summer. Temperatures were 0.9 °C above the long-term average. In 2021, weather conditions were similar to the previous year, with above-average temperatures in the growing season and sufficient precipitation.

2.1.2. Experimental Site B

Site B is located in the tertiary hill country, a hilly landscape in southern Bavaria (30 km north of Munich). Tertiary sediments are overlain by a thin loess cover. The site is

strongly heterogeneous and characterized by silt and clay lenses below the loess cover. The soils of the investigated arable fields are classified as Haplic Luvisols, with highly varying textures from loamy sand to loamy clay.

The long-term average temperature and precipitation for site B are 8.6 °C and 790 mm per year, respectively. The year 2018 was extremely hot and dry. The years 2019, 2020, and 2021 were very mild, but more precipitation fell (similar to the long-term average). The year 2021 was a humid year, with 120 mm more precipitation than in average years. Meanwhile, 2022 was characterized by a warm, dry spring until the end of April and enough precipitation until July (Table S2).

2.2. Management of the Investigated Fields

The investigated fields were cultivated by different organic farms using different organic cropping systems. The study fields were selected according to criteria for size, crop rotation, and management data availability. The fields were over 4 hectares in size (above-average sizes in the regions). All fields were cultivated with winter wheat, a crop that has been subject to many investigations in the application of digital methods in conventional systems. Furthermore, grass–clover had to be sown two years before the investigations to enable the evaluation of nitrate leaching after grass–clover plowing by deep drilling.

2.2.1. Site A, Dairy Farm, Field ‘A1’

Farm A is a commercial dairy farm with 1.8 livestock units per hectare. The crop rotation is a grass–clover mixture to grass–clover mixture to silage maize to winter wheat (Table 1). Thus, the proportion of grass–clover is 50%. Grass–clover is cut four to five times and used as forage in dairy farming. The straw of winter wheat is harvested. Organic fertilization with farmyard manure in the crop rotation is mainly applied to silage maize and winter wheat. The grass–clover management with intensive cutting and low nitrogen fertilization (10–12 m³ slurry to the start of the vegetation) results in high clover proportions of over 70%.

2.2.2. Site B, Arable Farm, Fields B1 and B2

Farm B is an experimental organic arable farm. The crop rotation is winter wheat to mixture—winter wheat—winter rye (Table 1). Thus, the proportion of grass–clover is 25%. Grass–clover is mulched three times per vegetation period. Grain straw is used as straw manure. There is no other organic fertilizer in the crop rotation. The proportion of clover in the grass–clover mixture is about 60% on average.

2.3. Digital Methods to Determine Plant Parameters and Ground Truth Data

2.3.1. Tractor-Mounted Sensor Data (Vegetation Index REIP)

A tractor-mounted multispectral sensor was used to measure the reflectance of winter wheat at flowering. Selected wavelengths from these measurements were used to calculate the red edge inflection point (REIP) vegetation index (Equation (1)), which is appropriate to estimate plant parameters such as yield and N uptake [27,28].

$$\text{REIP} = R700 + 40 [(R670 + R780)/2 - R700]/(R740 - R700) \quad (1)$$

The REIP vegetation index and crop-specific algorithms were applied to determine the N uptake of winter wheat non-invasively [8,24].

2.3.2. Satellite and Model Data (PROMET Model)

Based on satellite data from Sentinel 2, yields were modeled on a 10 × 10 m grid using the PROMET model [25]. PROMET is a hydro-agroecological model that uses remote sensing data for yield estimation [29].

2.3.3. Satellite Data (Multi-Year Biomass Potential Maps)

Data from the Sentinel-2 satellite [30] were used to calculate the normalized difference vegetation index (NDVI) (Equation (2)) in a 10×10 m grid.

$$\text{NDVI} = \lambda_{\text{NIR}} - \lambda_{\text{R}} / \lambda_{\text{R}} + \lambda_{\text{R}} \quad (2)$$

The NDVI is a good indicator to estimate above-ground plant biomass [31–34].

The multi-year biomass potential maps were calculated in the following way [35]: (1) Selection of two dates in the growing season relevant to each crop species in the crop rotation (without clouds in the image). For winter wheat and winter rye, the dates were chosen in the period from March to April, from June to July for silage maize, and one date before each cutting or mulching for grass–clover. (2) Calculation of the mean NDVI of each crop for every 10×10 m raster and calculation of the mean NDVI of each crop for the whole field. (3) Calculation of the relative NDVI of each crop for every raster element by dividing the mean NDVI for each raster by the mean NDVI of the field. (4) Calculation of the mean relative NDVI for each raster element of all crops (description of the methodology in Table S3).

The multi-year relative NDVI maps approximately characterize the site-specific relative biomass potential; they are called relative biomass potential maps (relBMPmaps). These relBMPmaps were used to identify zones with different biomass potentials within uniformly cultivated arable fields.

Crop yields for each raster element were calculated from the relative distribution of the NDVI in combination with measured data (the mean yield of the field, determined at the weighbridge). The yield data were used to calculate site-specific N balances (see Section 2.4).

2.3.4. Ground Truth Data

Measurement data (ground truth data) were obtained to validate the digitally determined yield data.

At site A, 28 biomass samples were taken, and the DM yield and N content of the biomass were determined in laboratory analyses. In addition, the yield was recorded at the weighbridge in 2021.

The georeferenced biomass samples were cut by hand using cordless clippers close to the ground. The grain was threshed in a laboratory thresher. The grain dry matter (DM) content was determined after drying at 60°C , and the grain yields in t ha^{-1} , based on 86% DM, were calculated. Grain N content was determined using a C/N Analyzer.

At site B, yield data from the yield measurement system of a combine harvester and mean yields from the weighbridge (in 2021 and 2022) were used as reference data. The combine harvester was calibrated to obtain accurate data.

The methods used are presented in Table S3.

2.4. Site-Specific N Balancing

N balancing was carried out according to the method implemented in the REPRO model to enable the assessment of N loss risks at the sub-field level of arable land.

Changes in the soil organic nitrogen stock (ΔSON) are included in the calculation of N balances. The algorithm for estimating ΔSON depending on site conditions, crop rotation, crop yield, and mineral and organic fertilization is described in and Table S4.

N balances ($\text{kg ha}^{-1} \text{ yr}^{-1}$) for each 10×10 m grid element were calculated:

$$\text{N surplus} = \text{N input} - \text{N output} - \Delta\text{SON} * \quad (3)$$

$$\text{N input} = \text{N deposition} + \text{N in farmyard manure} + \text{N}_2 \text{ fixation} * \quad (4)$$

$$\text{N output} = \text{N uptake (main product)} + \text{N uptake (by-product, if harvested)} \quad (5)$$

The balancing methods are described in detail in Table S4.

The N input consisted of the total nitrogen supplied with the organic fertilizers, the symbiotically fixed nitrogen, and a mean N deposition of $20 \text{ kg ha}^{-1} \text{ yr}^{-1}$ [36]. Organic nitrogen fertilizers (Table S4) were applied uniformly and in accordance with legal regulations.

Biological N_2 fixation by grass–clover was calculated, distinguishing between the amounts of nitrogen in harvested products and those in residues. It was assumed that N_2 fixation rises with increasing yield [37].

Changes in soil organic nitrogen (ΔSON) were calculated according to Leithold et al. [38] and Küstermann et al. [39,40]. This method estimates, in a simplified way, the change in the soil humus stock based on crop-specific effects depending on site conditions, yield level, mineral fertilization, and organic fertilization.

The N output corresponds to the N content of the harvested products (e.g., grain or silage corn), determined digitally or by measurements.

2.5. Methods of Determining Soil Properties

Georeferenced soil samples were taken from the investigated fields. The distribution of the soil samples within the field was ‘stratified random’. About 10 random points were sampled and georeferenced per hectare [41]. Eight soil samples were taken within a 50 cm maximum radius around a georeferenced point. All eight samples were combined into one composite sample.

Nitrate (NO_3) stocks in deeper soil layers were determined using a tractor-mounted hydraulic deep drilling rig [42] to generate georeferenced deep drillings. The boreholes were carried out to a depth of 3 m; and the core samples were divided into 50 cm thick layers. Nitrate content was analyzed photometrically [43] for each layer.

2.6. Descriptive Statistics

The mean, median, minimum, maximum, and standard deviation were calculated for variables using R4.1.1 [44].

2.7. Geostatistical Analysis

The site-specific measured data were transferred to grids of the same resolution ($10 \times 10 \text{ m}$) and with the same raster elements, raster input data by downsampling, and point input data by interpolation to the raster elements using ordinary kriging ($10 \times 10 \text{ m}$) [45]. A variogram (variance of the data according to distance classes) of the data was created, which showed the spatial relationship of the variable with increasing separation distance (spatial auto-correlation effect; semivariograms of kriged data are shown in Figures S1 and S2). A model was fitted to the variogram, which is used for weighting data in the kriging neighborhood to predict values at unsampled places [45]. The outer 10 m of the field was not included in the data analysis to avoid evaluating data from areas that did not belong to the field.

A correlation analysis based on the grid elements was performed to check the relationship between the plant and soil variables. The R libraries ‘rgdal’, ‘rgeos’, ‘gstat’, and ‘raster’ were used for spatial analyses and loading vector or raster files. The correlation coefficients (r) were classified as very strong ($r > 0.9$), strong ($0.9 > r > 0.7$), moderate ($0.7 > r > 0.5$), weak ($0.5 > r > 0.3$), or very weak ($r < 0.3$).

Figure 1 includes a flowchart that shows the consecutive work steps for determining plant and N balance variables and soil properties, as well as the subsequent geostatistical and correlation analysis.

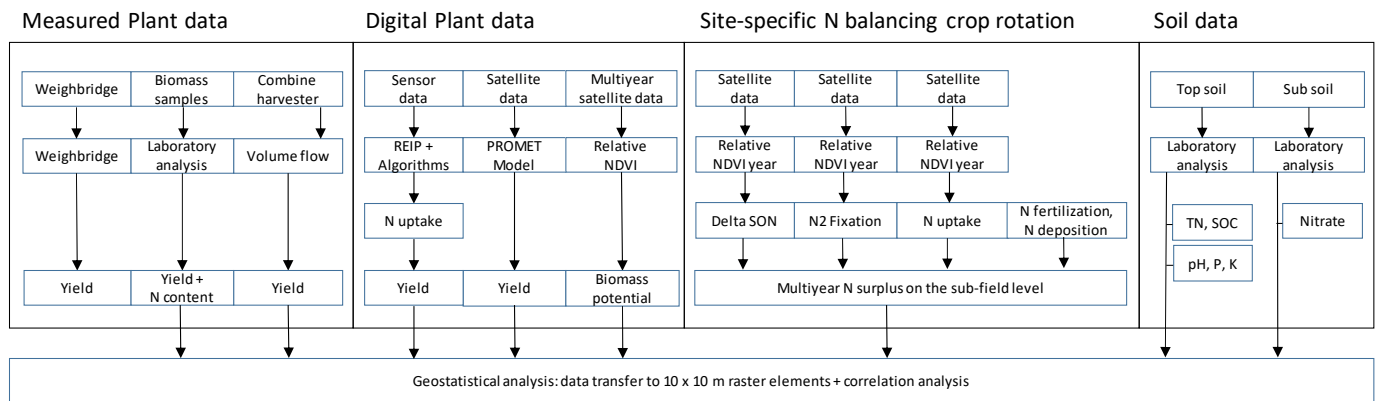


Figure 1. Flow chart of the consecutive work steps in this study.

3. Results

3.1. Soil Properties

There was great variability in the measured soil properties in the study fields.

The soil of field A (dairy farm) had a mean SOC content of 1.56% (1.41 to 1.77) with a standard deviation of 0.08 (Table 2). The soils of the arable farm at site B had lower mean SOC contents on the two fields of investigation (B1: 1.17%, SD 0.17%; B2: 1.35%, SD 0.28). Similar to other parameters, site B had greater soil heterogeneity with higher SOC contents in hollows. The mean C/N ratio at site A was slightly higher (9.8:1) than at site B (9.6:1).

Table 2. Descriptive statistics of the soil data acquired in Field A1 (site A) and Field B1 and B2 (site B).

Soil Properties	n	Unit	Mean	Median	Min	Max	SD	Skewness
<i>Site A, field A1</i>								
Soil organic carbon content (0–30 cm)	28	% DM	1.56	1.56	1.41	1.77	0.08	0.45
Soil total nitrogen content (0–30 cm)	28	% DM	0.16	0.16	0.14	0.18	0.01	0.50
Nitrate concentration (0–3 m)	14	mg L ^{−1}	16.9	15.7	8.3	24.7	5.3	0.03
P (0–30 cm)	28	mg (100 g) ^{−1}	7.7	7.4	5.4	10.7	1.3	0.52
<i>Site B, field B1</i>								
Soil organic carbon content (0–30 cm)	27	% DM	1.17	1.20	0.77	1.52	0.17	−0.74
Soil total nitrogen content (0–30 cm)	27	% DM	0.12	0.13	0.08	0.15	0.02	−1.09
Nitrate concentration (0–3 m)	22	mg L ^{−1}	6.5	5.5	2.2	17.5	4.0	1.25
P (0–30 cm)	27	mg (100 g) ^{−1}	3.9	3.5	1.5	8.0	1.7	1.39
<i>Site B, field B2</i>								
Soil organic carbon content (0–30 cm)	43	% DM	1.35	1.28	0.75	1.90	0.28	0.29
Soil total nitrogen content (0–30 cm)	43	% DM	0.15	0.14	0.08	0.21	0.03	0.33
P (0–30 cm)	43	mg (100 g) ^{−1}	4.9	4.4	1.9	10.0	2.3	0.86

Nitrate concentrations in leakage water at both sites (site A: 16.9 mg L^{−1}; site B: 6.5 mg L^{−1}) were clearly below the maximum threshold of 50 mg L^{−1}. There was spatial variability of the nitrate concentrations, but all mean concentrations in 0 to 3 m were below 25 mg L^{−1} at site A and 18 mg L^{−1} on site B.

P contents in 0 to 30 cm at site B were lower than at site A. Field A had a P content of 5.7 (5.4–6.5) mg (100 g)^{−1}. At site B, field B1 had a P content of 3.6 (1.5–8.0) mg (100 g)^{−1}, and field B2 had a P content of 4.9 (1.8–10.0) mg (100 g)^{−1}.

3.2. Yields

Yields of winter grains (winter wheat and winter rye) were determined because digital methods were also validated for these crops in conventional systems. Furthermore, these crops, especially winter wheat, are important in conventional farming as well as organic farming and were cultivated on farms A and B.

3.2.1. Site A, Dairy Farm, Field A1

At field A1, wheat yields in 2021 were determined using four different methods: (a) at the weighbridge, (b) via biomass sampling and laboratory analysis, (c) with the PROMET model, and (d) with a tractor sensor. Thus, a comparison of the results of the different methods is possible (Table 3). The mean yield at the weighbridge (6.8 t ha^{-1}) is the same as that determined by the tractor sensor. The biomass samples and the Promet model resulted in slightly lower mean yields. The yield variability recorded with the tractor sensor was the highest; yields varied from 3.8 to 10.6 t ha^{-1} . However, it should be noted that this system also had the greatest number of measuring points ($n = 945$). The N uptake determined with different measuring systems also agreed well (mean 103 to 111 kg ha^{-1}). According to the measurements with the tractor sensor, the N uptake was 61 to 170 kg ha^{-1} (Table 3). A point-to-point comparison between biomass samples and digital methods showed stronger correlations than a correlation analysis between kriged data.

Table 3. Yield and N uptake of winter wheat, field A1.

Plant Variable	Data Source	<i>n</i>	Unit	Mean	Minimum	Maximum	Standard Deviation	Skewness
<i>2021, A1, winter wheat^{ab}</i>								
Grain yield	Weighbridge	1	t ha^{-1}	6.8				
Grain yield	Biomass samples	28	t ha^{-1}	6.4	5.2	8.3	0.6	0.76
Grain yield	Model PROMET	435	t ha^{-1}	6.5	3.3	8.0	0.8	−1.70
Grain yield	Tractor sensor	945	t ha^{-1}	6.8	3.8	10.6	1.1	−0.10
Grain N uptake	Weighbridge	1	kg ha^{-1}	111				
Grain N uptake	Biomass samples	28	kg ha^{-1}	103	75	153	15	1.28
Grain N uptake	Tractor sensor	945	kg ha^{-1}	110	61	170	17	−0.05

^a moisture content of winter wheat, 14%; ^b N content, 1.9%.

The closest correlation to the measured yield (biomass samples) was shown by the tractor sensor ($r = 0.58$); the relBMPmaps method also achieved a moderate relationship ($r = 0.56$), while the PROMET model only showed a weak correlation ($r = 0.39$). The correlation between biomass samples and tractor sensors was also best for N uptake, while that with the PROMET model was worst (Table 4).

Table 4. Correlation matrix (*r*) of digitally determined and measured plant parameters based on a $10 \text{ m} \times 10 \text{ m}$ raster, field A1.

<i>r</i>	Grain Yield Biomass Samples (<i>n</i> = 28)	N Uptake Biomass Samples (<i>n</i> = 28)	Model PROMET (<i>n</i> = 404)	relBMPmap (<i>n</i> = 404)
<i>Field A1, winter wheat 2021 (<i>n</i> = 28 (point to point), <i>n</i> = 404 kriged raster)</i>				
Tractor sensor	0.58	0.66	0.38	0.65
Model PROMET	0.39	0.34		0.41
relBMPmap	0.56	0.58		

The spatial variability and distribution patterns of the digitally determined soil and plant parameters and the validation data from field A1 are shown in Figure 2.

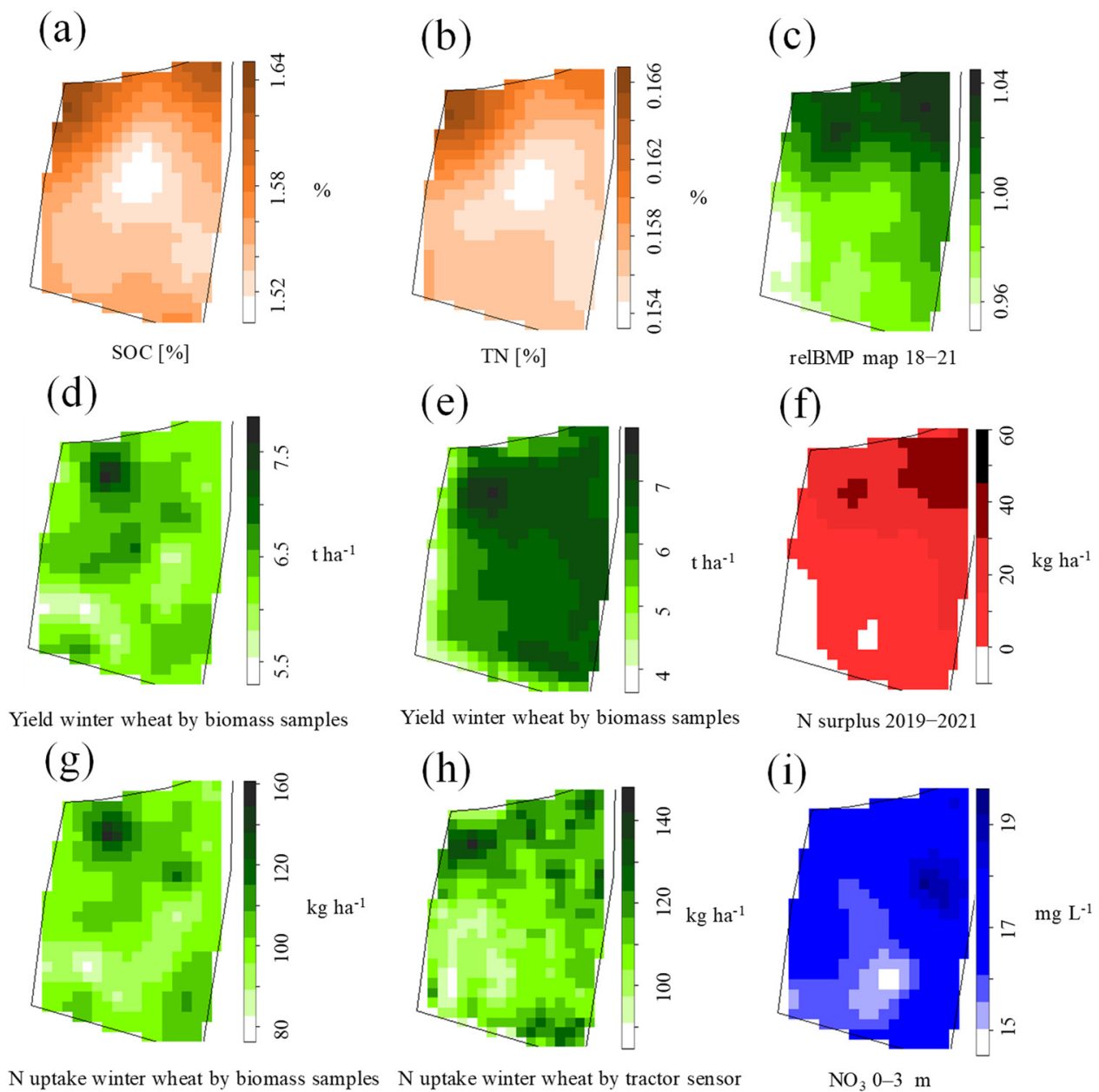


Figure 2. Kriged maps of the spatial distribution of (a) SOC (%), (b) TN (%), (c) relBMPmap 18–21, (d) yield plant samples (t ha^{-1}), (e) yield model PROMET (t ha^{-1}), (f) N surplus multi-year relBMPmap 2018–2021 (kg ha^{-1}), (g) N uptake plant samples (kg ha^{-1}), (h) N uptake tractor sensor (kg ha^{-1}), and (i) nitrate concentration in 0–3 m (mg L^{-1}) at field A1.

3.2.2. Site B, Crop Farm, Fields B1, B2

At site B, the digital systems tractor sensor, model PROMET, and relBMP were validated by data from a calibrated yield measurement system on the combine harvester as well as measured values at the weighbridge in 2021 and 2022 (Table 5).

The mean yields agree well in 2022; in 2021, the yield was significantly overestimated with the PROMET model (6.1 t ha^{-1}) compared to 3.9 t ha^{-1} (Weighbridge, Harvester).

The yield variability at site B was greater than at site A. The yield level at site B was considerably lower than at site A. The descriptive statistics of site B are shown in Table 5.

Table 5. Yields, study field B1 and B2.

Plant Variables	Data Source	<i>n</i>	Unit	Mean	Minimum	Maximum	Standard Deviation	Skewness
<i>2021, B1, winter wheat^a</i>								
Grain yield	Weighbridge	1	t ha ^{−1}	3.9				
Grain yield	Combine harvester	9068	t ha ^{−1}	3.9	1.5	6.2	1.0	−0.03
Grain yield	Model PROMET	1488	t ha ^{−1}	6.1	3.4	9.2	1.1	−0.23
<i>2022, B1, winter rye^b</i>								
Grain yield	Weighbridge	1	t ha ^{−1}	4.8				
Grain yield	Combine harvester	7986	t ha ^{−1}	4.7	2.1	7.2	1.1	0.10
Grain yield	Tractor sensor	1472	t ha ^{−1}	4.7	3.1	9.1	0.8	0.99
<i>2022 B2, winter wheat^c</i>								
Grain yield	Weighbridge	1	t ha ^{−1}	4.0				
Grain yield	Combine harvester	5168	t ha ^{−1}	4.3	1.6	7.5	1.2	0.17
Grain yield	Tractor sensor	1228	t ha ^{−1}	4.6	2.0	8.4	1.3	0.60

^a moisture content of winter wheat and rye, 14%; ^b N content, 1.8%; ^c N content, 2.2%.

On fields B1 and B2 (site B), the data determined with digital methods showed moderate to strong correlations to combine harvester data (0.60, 0.77). Tractor sensor data and relBMPmap data correlated strongly (0.75 and 0.86), and model PROMET data and relBMPmap data correlated very strongly (0.90) (Table 6).

Table 6. Correlation matrix (*r*) of digitally determined and measured plant parameters based on a 10 m × 10 m raster, fields B1 and B2.

R	Combine Harvester 21	Combine Harvester 22	relBMPmap
<i>Field B1, winter wheat 21 (n = 378 kriged raster)</i>			
Model PROMET	0.71	0.60	0.90
<i>Field B1, winter rye 22 (n = 378 kriged raster)</i>			
Tractor sensor	0.67	0.73	0.75
relBMPmap	0.68	0.64	
<i>r</i>	Combine harvester 18	Combine harvester 22	relBMPmap
<i>Field B2 winter wheat 22 (n = 419 kriged raster)</i>			
Tractor sensor	0.72	0.76	0.86
relBMPmap	0.67	0.77	

The spatial variability and distribution patterns of the digitally determined soil and plant parameters and the validation data from fields B1 and B2 are shown in Figures 3 and 4. In this field, the yield patterns determined with different methods were very similar, even in different years with different crops.

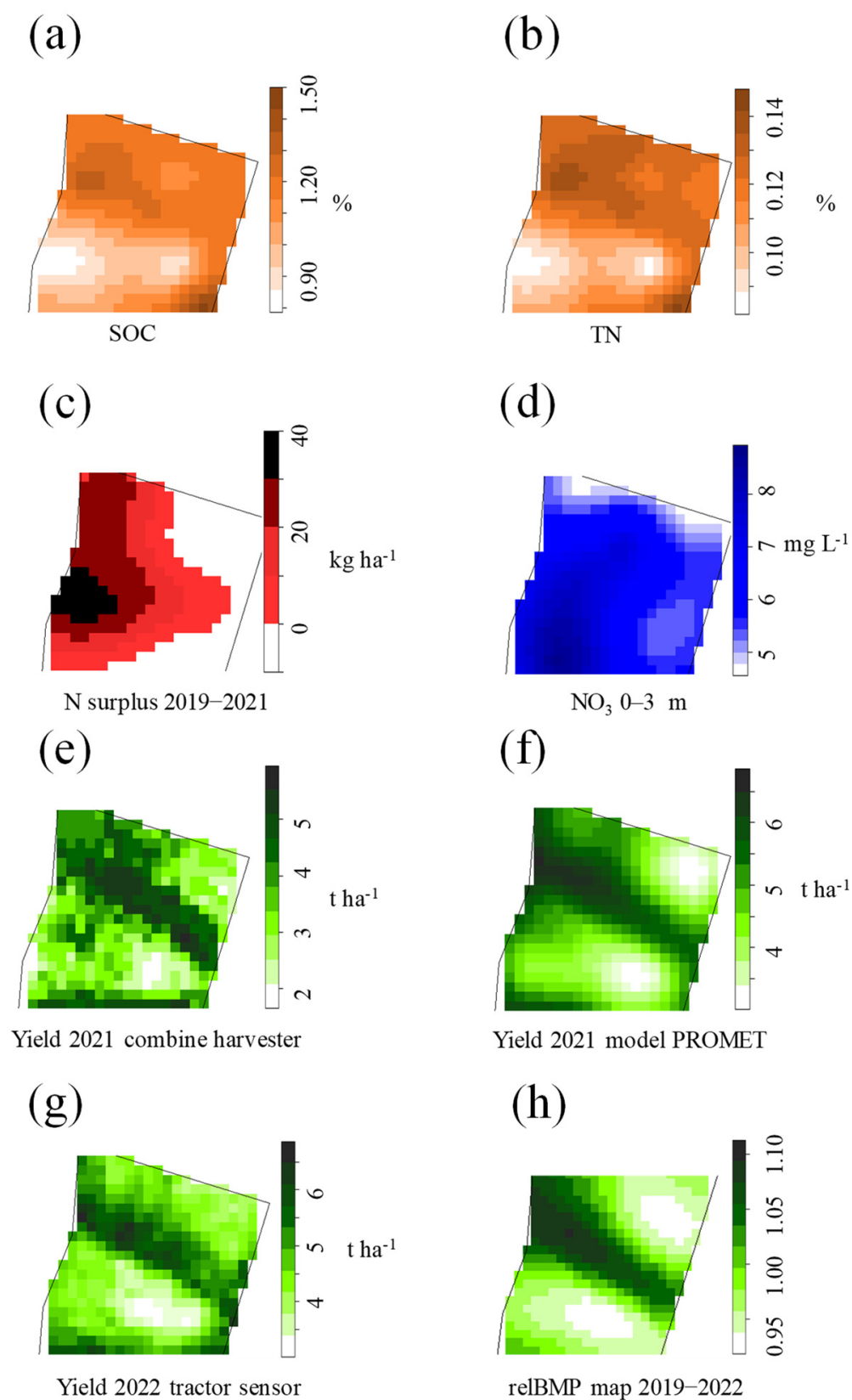


Figure 3. Kriged maps of the spatial distribution of (a) SOC (%), (b) TN (%), (c) N surplus multi-year relBMPmap 2019–2022 (kg N ha⁻¹), (d) nitrate concentration in 0–3 m (mg L⁻¹), (e) relBMPmap 19–22, (f) yield combine harvester (t ha⁻¹), (g) yield model PROMET (t ha⁻¹) and (h) yield tractor sensor (t ha⁻¹) at field B1.

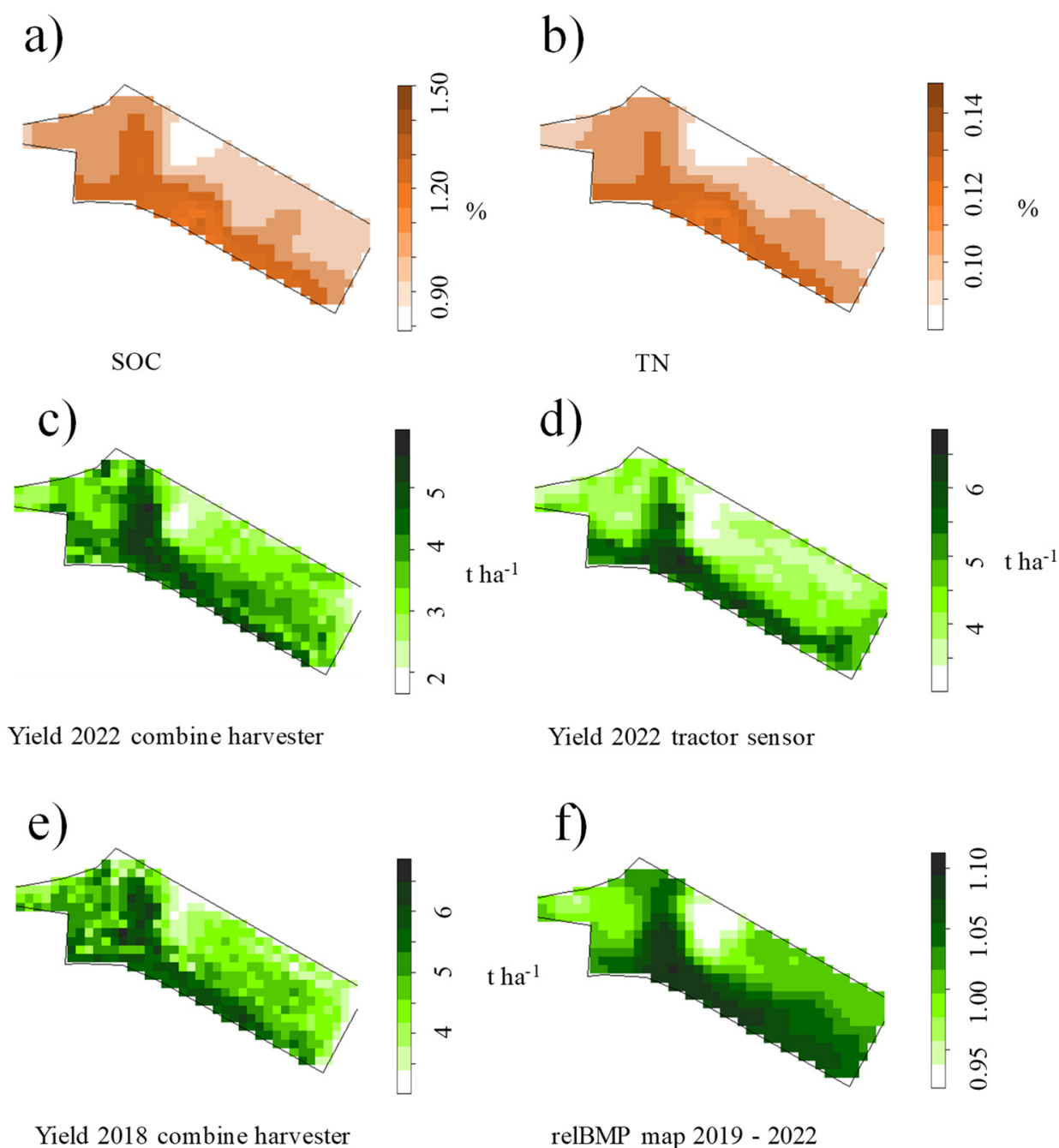


Figure 4. Kriged maps of the spatial distribution of (a) SOC (%), (b) TN (%), (c) 22 yield combine harvester 2022 (t ha^{-1}), (d) yield tractor-sensor (t ha^{-1}), (e) yield combine harvester 2018 (t ha^{-1}), (f) relBMPmap19- at field B2.

3.3. Site-Specific N Balancing Based on Multi-Year relBMP Maps

Based on the N balancing method described in Section 2.4, using the NDVI determined with satellite data, N balances were calculated for the study years for each $10 \times 10 \text{ m}$ grid 8 (Table 7).

Table 7. Site-specific N balancing for the study field A1 2018–2021 (n = 404).

N Balance	Parameter	Data Source *	Unit	Mean	Minimum	Maximum	Standard Deviation
2018; Grass-clover mixture; 4 cuts, FM yield 45 t ha⁻¹, clover proportion 60–80%							
<i>N input</i>	N fertilization	15 m ³ slurry ha ⁻¹ , 4.2 kg N (m ³) ⁻¹	kg ha ⁻¹	63			
<i>N input</i>	N ₂ Fixation	Satellite data + model	kg ha ⁻¹	279	232	353	28
<i>N output</i>	N uptake	Satellite data + weighbridge	kg ha ⁻¹	270	239	316	18
Δ SON		Satellite data + model	kg ha ⁻¹	105	98	114	4
<i>N surplus</i>	2018		kg ha ⁻¹	−13	−22	6	7
2019; Grass-clover mixture; 4 cuts, FM yield 55 t ha⁻¹, clover proportion 60–80%							
<i>N input</i>	N fertilization	12 m ³ slurry ha ⁻¹ , 3.5 kg N m ³	kg ha ⁻¹	42			
<i>N input</i>	N ₂ Fixation	Satellite data + model	kg ha ⁻¹	389	348	429	18
<i>N output</i>	N uptake	Satellite data + weighbridge	kg ha ⁻¹	330	307	352	10
Δ SON		Satellite data + model	kg ha ⁻¹	129	124	134	2
<i>N surplus</i>	2019		kg ha ⁻¹	−8	−21	5	6
2020; Grass-clover mixture, 1 cut May 2020, FM yield 20 t ha⁻¹, clover proportion 70%; following silage maize, FM yield 50 t ha⁻¹							
<i>N input</i>	N fertilization	24 t dung ha ⁻¹ , 6 kg N t ⁻¹	kg ha ⁻¹	144			
<i>N input</i>	N ₂ Fixation	Satellite data + model	kg ha ⁻¹	136	125	149	6
<i>N output</i>	N uptake	Satellite data + weighbridge	kg ha ⁻¹	327	294	349	12
Δ SON		Satellite data + model	kg ha ⁻¹	−26	−45	−2	11
<i>N surplus</i>	2020		kg ha ⁻¹	−5	−6	−1	1
2021; Winter wheat, FM yield 6.5 t ha⁻¹							
<i>N input</i>	N fertilization	22 m ³ slurry ha ⁻¹ , 4 kg N (m ³) ⁻¹	kg ha ⁻¹	88			
<i>N output</i>	N uptake	Satellite data + weighbridge	kg ha ⁻¹	105	96	113	4
Δ SON		Satellite data + model	kg ha ⁻¹	−38	−46	−28	5
<i>N surplus</i>	2021		kg ha ⁻¹	40	40	41	1
Crop rotation 2018–2021							
<i>N input</i>	N fixation	Satellite data + model	kg ha ⁻¹	201	177	227	12
<i>N output</i>	N uptake	Satellite data + weighbridge	kg ha ⁻¹	258	234	279	10
Δ SON		Satellite data + model	kg ha ⁻¹	42	36	50	3
<i>N surplus</i>	2018–2021		kg ha ⁻¹	15	−8	44	2

* methods description in Table S4.

3.3.1. Site A, Dairy Farm, Field A1 2018–2021 (Grass–Clover Mixture to Grass–Clover Mixture to Silage Maize to Winter Wheat)

The main N input source at field A1 was the symbiotic N₂ fixation of the multi-year grass–clover mixture (two years of cultivation and one cut in the spring of the third year). The calculated symbiotic N₂ fixation reached 270 kg ha⁻¹ in 2018 and 389 kg ha⁻¹ in 2019 and ranged from 232 kg ha⁻¹ to 429 kg ha⁻¹ with a higher N₂ fixation in high-yield zones (Table 7).

The nitrogen in the grass–clover forage was transferred to the dairy barn. Dairy cattle slurry was mainly used for non-legume crops (slurry N input, silage corn 2020: 144 kg ha⁻¹; winter wheat 2021: 88 kg ha⁻¹). A total of 20 kg ha⁻¹ a⁻¹ was assumed as N input due to atmospheric N deposition (a detailed description is provided in Table 7).

Grass–clover caused a modeled increase in SON (2018: 105 kg ha⁻¹, 2019: 129 kg ha⁻¹) with greater increases in high-yield zones. In contrast, for silage maize and winter wheat, a decrease in SON was calculated with the model in the years 2020 and 2021. In summary, in the four years, a mean increase in SON of 170 kg ha⁻¹ was modeled, which was 42 kg ha⁻¹ a⁻¹.

The N uptake of all crops was higher in high-yield zones, leading to a lower N surplus in these zones and a higher N surplus in low-yield zones. The mean N uptake in the crop rotation was 258 kg ha⁻¹ with a range of 234 kg ha⁻¹ to 279 kg ha⁻¹.

The spatial variability of the N surplus in single years was relatively low, as the effects of varying N inputs, N outputs (crop N uptake), and changes in SON balanced each other. In total, the crop rotation N surplus varied from −8 kg ha⁻¹ to 44 kg ha⁻¹ (mean 15) and thus was well-balanced. The non-legume crops, wheat and maize, used nitrogen from N₂ fixation and therefore achieved relatively high yields.

3.3.2. Site B, Crop Farm, Field ‘B1’ 2019–2022 (Winter Wheat to Grass–Clover Mixture to Winter Wheat to Winter Rye)

N₂ fixation was the dominant N input at farm B. In some years, the farm received slurry from another organic dairy farm, which was applied to winter wheat (15 m³ of slurry in 2019). The N₂ fixation of the two- to three-times mulched grass–clover mixture (242 kg N ha⁻¹) was considerably lower than the N₂ fixation at site A and varied from 150 kg N ha⁻¹ to 320 kg N ha⁻¹. Thus, in the four years of the crop rotation, N input by N fixation at site B was 61 kg N ha⁻¹ and varied from 39 kg N ha⁻¹ to 79 kg N ha⁻¹. The mean N fixation in the crop rotation at field A was significantly higher (mean: 201 kg N ha⁻¹, minimum: 177 kg N ha⁻¹, and maximum: 227 kg N ha⁻¹).

The mean ΔSON in the crop rotation (B1: mean: 10 kg ha⁻¹, minimum: 5 kg ha⁻¹, and maximum: 15 kg ha⁻¹) was lower than at field A1 (A1: mean: 42 kg ha⁻¹, minimum: 36 kg ha⁻¹, and maximum: 50 kg ha⁻¹) because grass–clover was grown only once in the four years of crop rotation. Over the crop rotation, ΔSON was higher in high-yield zones.

N uptake in all crops was higher in high-yield zones. The mean N uptake in the crop rotation was 86 kg ha⁻¹, with a range from 73 kg ha⁻¹ to 103 kg ha⁻¹. N uptake was considerably lower than at site A (mean: 258 kg ha⁻¹, 234–279 kg ha⁻¹). This is primarily due to lower N inputs (less clover grass in the crop rotation, lower N₂ fixation of grass–clover, and lower organic fertilization). The crop rotation resulted in a well-balanced mean N surplus of 1 kg ha⁻¹ and varied from −34 kg ha⁻¹ to 29 kg ha⁻¹. All N balance parameters and their variability are shown in Table 8.

Table 8. Site-specific N balancing for the study field B1 2019–2022 (n = 378).

N Balance	Parameter	Data Source *	Unit	Mean	Minimum	Maximum	Standard Deviation
<i>2019; Winter wheat, FM yield 4.6 t ha⁻¹</i>							
N input	N fertilization	Calculation	kg ha ⁻¹	63			
N output	N uptake	Satellite data + weighbridge	kg ha ⁻¹	80	52	105	15
	ΔSON	Satellite data + model	kg ha ⁻¹	−27	−42	−14	8
N surplus	2019		kg ha ⁻¹	31	−37	48	8
<i>2020; Grass-clover mixture; 1. cut, FM yield 19 t ha⁻¹, clover proportion 60%, 2 cuts green manure</i>							
N input	N ₂ Fixation	Satellite data + model	kg ha ⁻¹	242	154	316	41
N output	N uptake	Satellite data + weighbridge	kg ha ⁻¹	114	85	137	13
	ΔSON	Satellite data + model	kg ha ⁻¹	118	101	130	7
N surplus	2020		kg ha ⁻¹	29	−12	72	21
<i>2021 Winter wheat, 3.9 t ha⁻¹</i>							
	N uptake	Satellite data + weighbridge	kg ha ⁻¹	74	55	95	11
	ΔSON	Satellite data + model	kg ha ⁻¹	−25	−36	−15	6
N surplus	2021		kg ha ⁻¹	−29	−38	7	6

Table 8. Cont.

N Balance	Parameter	Data Source *	Unit	Mean	Minimum	Maximum	Standard Deviation
<i>2022; Winter rye, FM yield 5.5 t ha⁻¹</i>							
	N uptake	Satellite data + weighbridge	kg ha ⁻¹	76	69	83	4
	Δ SON	Satellite data + model	kg ha ⁻¹	−25	−30	−21	2
<i>N surplus</i>	2022		kg ha ⁻¹	−30	−33	−28	1
<i>Crop rotation 2019–2022</i>							
<i>N input</i>	N fixation	Satellite data + model	kg ha ⁻¹	61	39	79	10
<i>N output</i>	N uptake	Satellite data + weighbridge	kg ha ⁻¹	86	73	103	9
Δ SON		Satellite data + model	kg ha ⁻¹	10	5	15	3
<i>N surplus</i>	2019–2022		kg ha ⁻¹	1	−34	29	16

* methods description in online Table S4.

3.4. Soil Properties Related to Yields and N Surpluses

The kriged data of measured soil properties were related to digitally determined data. In all fields, SOC was moderately to strongly correlated with multi-year satellite data (A1: $r = 0.53$, B1: $r = 0.51$, B2: $r = 0.74$). TN was also positively related to relBMPmaps at a comparable level.

P content of fields A1 and B1 was positively correlated to SOC ($r = 0.58$, $r = 0.57$); in field B2, the correlation was negative ($r = -0.50$). Correspondingly, P correlated positively with the plant parameters of fields A1 and B1 and negatively with those of field B2.

Nitrate concentrations had a weak positive correlation to SOC and TN in field A1 and a moderate negative correlation in field B1. On both fields, the site-specific calculated N surpluses positively correlated to nitrate concentrations (A1: $r = 0.66$, B1: $r = 0.50$). The strongest impacts on nitrate concentrations in leakage water at field A1 were caused by the N balance parameters N₂ fixation in 2018 ($r = 0.55$) and 2019 ($r = 0.64$) and Δ SON ($r = 0.46$, $r = 0.55$). Spatial nitrate concentrations were higher in high-yield zones with higher N₂ fixation and greater changes in SON. In field B1, the effects were less clear. The effect of winter wheat (N balance parameter Δ SON, $r = 0.53$) had the strongest influence on measured nitrate concentrations. N₂ fixation in the mulched grass–clover mixture had a weak correlation to nitrate concentration ($r = 0.25$). Correlations are shown in Table 9.

Table 9. Plant parameters determined using digital methods related to ground truth data *, Correlation matrix (r) based on 10 m $\times$ 10 m raster.

Site A	SOC	Nitrate Concentration 0–3 m	relBMPmap 2018–2021
Field A1 ($n = 404$ kriged raster)			
N surplus 18–21	0.47	0.66	0.84
TN	0.94	0.17	0.53
SOC		0.34	0.65
Site B	SOC	Nitrate concentration 0–3 m	relBMPmap 2019–2022
Field B1 ($n = 378$ kriged raster)			
N surplus 19–22	−0.29	0.50	0.35
TN	0.97	−0.49	0.59
SOC		−0.56	0.51
Field B2 * ($n = 419$ kriged raster)			
TN	0.98		0.73
SOC			0.74

* no deep drillings and N balancing.

4. Discussion

4.1. Site Selection

This study aimed to test the digital methods at different sites and under different conditions. Site-specific differences in yield and N efficiency within arable fields are caused and influenced by physical, chemical, and biological soil properties; soil genesis; and cultivation (crop rotation, tillage, and fertilization) [46,47]. Two contrasting sites and farms were chosen to test digital methods under different conditions. Caused by topography and soil genesis, the tertiary hill country had a stronger heterogeneity than the smooth hilly landscape at site A, where the heterogeneity was predominantly caused by a varying skeletal proportion in the top- and sub-soil [22]. At site A, the strong texture heterogeneity in the sub-soil causes lateral water flows. The field management of the two farms showed clear differences. The more intensively managed field A1 of farm A was characterized by higher grass–clover proportions in the crop rotation and more organic fertilization than the fields B1 and B2 of farm B without animal stocks.

4.2. Discussion of Methods

The tested digital methods used (tractor-mounted multispectral sensors, perennial satellite data, vegetation indices, and models) are suitable for estimating yields in organic agriculture and showed similar correlations to investigations in conventional systems [11]. The digitally determined mean yields also agreed well with ground-truth data ($\pm 10\%$ of measured data, determined by the weighbridge, plant samples, and combine harvester, except for the model PROMET, yield estimation at field B1, 2021) (Tables 3 and 5).

The kriging of the digital data at a high spatial resolution resulted in a high semivariogram quality [45] (Figures S1 and S2). The kriging quality of the plant samples was lower. On average, 10 samples per hectare were insufficient to recognize yield zones well. Therefore, additional point-to-point correlations between digital methods and plant samples were calculated and showed stronger correlations (Table 4).

An innovation of this study is the site-specific N balancing based on a multi-year relative biomass potential map to analyze N fluxes and N pools in crop rotations. N input variables such as N_2 fixation and changes in SON were modeled at the sub-field level (10×10 m). Site-specific yield data (relBMPmap) was calculated using the relative distribution of the vegetation index NDVI based on satellite data. The approach for estimating biomass potential successfully used here and in other studies [22] needs to be further validated and, if necessary, adapted to specific crops.

N_2 fixation can vary greatly within croplands, as studies by Heuvelink et al. [48] show. N_2 fixation was calculated site-specifically depending on yield, clover proportions, and N content according to the method described by [49,50]. Using this approach, high N_2 fixation is calculated in high-yield areas.

According to [40,51], the consideration of changes in SON improves N balance quality. The influence of crop types in a crop rotation on Δ SON is calculated using a balancing method described by. Based on this modeling approach, SON and SOC accumulation increase with increasing clover–grass yield; thus, SOC is greater in high-yield zones than in low-yield zones.

These two N fluxes (N_2 fixation, Δ SON) led to higher N inputs and higher N surpluses in high-yield zones than in low-yielding zones. The site-specific calculated N surpluses were related to measured nitrate concentrations in leakage water. The correlations between calculated N surpluses and nitrate concentrations from deep drilling (field A1: $r = 0.66$, field B1: $r = 0.52$) indicate the suitability of the complex N balancing approach. Nevertheless, N balances are subject to numerous errors and inaccuracies [52], e.g., ammonia N losses were not quantified site-specifically. Additionally, measured nitrate concentrations can also be subject to errors. For example, there is also a spatial variability in the leaching rate within heterogeneous fields [22,53], and lateral water flows can complicate the interpretation of deep drilling results.

Therefore, it can be concluded that the N-balancing approach for organic crop rotations with legumes presented here needs to be further validated and adapted to different site conditions.

Satellite data have been available retrospectively for each agricultural area for many years. This is a major advantage over data from tractor-mounted sensor systems. With the approach of satellite-based site-specific N-balancing presented here, even long-term and complex crop rotations can be analyzed. The analysis of whole crop rotations is crucial in organic farming, as nitrogen supply depends on soil fertility and nitrogen transfer between crops within the crop rotation.

4.3. Spatial Variability of Yield Performance in Organic Agriculture

Mean digitally determined yields on site A were considerably higher than at site B (wheat yields $> 2.5 \text{ t ha}^{-1}$). Organic dairy farms have a higher NUE than organic arable farms [17]. Importantly, the grass–clover management of dairy farms affects the sustainable intensification of the nitrogen cycle. Cutting and harvesting grass–clover biomass, compared to green manuring of the grass–clover biomass, increases digitally determined yield and modeled nitrogen fixation [37,48,54]. Organic manure from dairy cows can be applied to crops with high nitrogen demands [17]. Thus, integrating dairy cows into organic farming systems increases yield performance [55].

Site B showed greater variability in all measured soil properties (SOC, TN, and P) and had higher variability in digitally determined crop yield than farm A. In farm B with low N inputs, digitally determined yields were more strongly influenced by soil fertility. In the high-yield zones of site B, yields were almost as high as at site A. Several publications are already available on the influence of important soil parameters, such as SOC and SON, on yield using digital technologies [11,23], but so far, none have been completed under the conditions of organic farming. The results of this study substantiate the results of other recent studies that have emphasized the importance of natural soil fertility on yields in organic farming at other levels, such as the field or the farm [56,57].

4.4. Environmental Performance and Spatial Variability of Soil Properties

Measured nitrate concentrations in leakage water were low at both sites. The deep drillings at both fields (A1, B1) were done two years after the plowing of the grass–clover mixture, which is a sensitive time for nitrogen losses [58,59], especially when tilling is practiced in autumn before the beginning of the leaching period. With a mean of 17 mg L^{-1} nitrate, the concentration was less than 50% of the concentration (40 mg L^{-1} nitrate) in the drinking water of the region (site A). With less than 7 mg L^{-1} nitrate (site B), the concentration was extremely low. Relatively high nitrate concentrations occurred in high-yield zones with high N_2 fixation and mineralization of SON. In contrast, very high nitrogen surpluses and nitrate losses in low-yielding zones in conventional farming were found in other studies at different sites. High and uniform mineral N fertilization was identified as the main cause [22].

Similar to other investigations in conventional systems [11], SOC had a moderate to strong positive influence on yields in organically managed systems. High-yield zones were characterized by higher SOC and TN contents; thus, SOC and TN are appropriate indicators of yield zones. This illustrates the importance of sufficiently high SOC and SON contents in agricultural fields. Site A, with higher grass–clover proportions and organic fertilization, had higher SOC contents than site B. However, besides the crop rotation and fertilization effects, there are also natural influences on humus content in soils (texture, topography, height, etc.).

5. Conclusions, Outlook, and Further Research

System comparisons between organic and conventional farming show significant yield differences [18]. Crop yields in organic farming are often limited by nutrient supplies such as nitrogen or phosphorus. To sustainably increase yields with limited availability

of nitrogen, the N inputs (N_2 fixation and organic manure) have to be used efficiently. A smart way to increase NUE is to use digital methods such as remote or proximate sensing.

The examination of the hypothesis yielded the following results:

Hypothesis 1. *Sensor- and satellite-based methods for determining site-specific crop yield and nitrogen uptake are applicable for crops in organic farming, particularly winter grains, and provide sufficiently accurate results.*

The correlations between yield and N uptake determined with digital systems and the validation data were up to $r = 0.77$. The mean yield determined with different digital methods was positively correlated with the ground-truth values. Therefore, Hypothesis 1 is accepted.

Hypothesis 2. *Remote sensing allows the calculation of nitrogen balances in organic crop rotations at the sub-field level to assess the risks of nitrogen losses. Calculated site-specific N balances are positively related to measured nitrate concentrations in leakage water from deep drilling.*

The digital data-based methodology for nitrogen balancing was used to determine site-specific N balances. The N balances were related to measured nitrate levels. The calculated N surpluses correlated positively with the nitrate concentrations in leakage water ($r = 0.50$, $r = 0.66$). Therefore, Hypothesis 2 is accepted.

Hypothesis 3. *In long-term organically managed arable fields, the soil carbon content is closely related to site-specific yields.*

SOC was moderately to strongly correlated to the digitally or manually determined plant parameters (yield and N uptake) in all study fields ($r = 0.50$ to $r = 0.74$). Hypothesis 3 is also accepted.

The digital determination of yields and the site-specific N balancing enable the analysis of yield and environmental performance of organic farming systems with high spatial resolution. This can be a promising method to gain site-specific plant and soil information as a basis for site-specific management decisions in organic farming, e.g., on fertilization, crop rotation, grass-clover management, or pest management. Especially organic farms at heterogeneous sites or farms with a lack of nutrients could benefit from such high-resolution data. In the next step, site-specific management decisions could be tested on organically managed arable fields derived from remote and proximal sensing technologies. Furthermore, the study shows the importance of natural soil fertility on yield performance in organic agriculture. This underlines the importance of a further increase in soil fertility in organically managed arable lands.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy13071868/s1>, Table S1: Mean temperature and precipitation at site A*, Table S2: Mean temperature and precipitation at site B*, Table S3: Methods description of soil and plant data, Figure S1: Variograms of (a) SOC content, (b) TN content, (c) yield tractor-sensor, (d) yield PROMET, (e) yield plant samples, (f) N uptake plant samples at field A1, Figure S2 Variograms of (a) SOC content, (b) TN content, (c) yield tractor-sensor, (d) yield PROMET, (e) yield combine harvester 2021, (f) yield combine harvester 2022 at field B1, Table S4: Methods description of N balancing.

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