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Posted Date: 2 November 2023

doi: 10.20944/preprints202311.0125.v1

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Abstract: The aim of the study was to verify whether a 20 and 40% reduction of nitrogen (N) fertilization rate will be sufficient to maintain soil basic chemical features, fertility, and yielding in monoculture maize cultivation in the no-tillage (NT) system versus the traditional plowing (PL) system. In addition, it was examined which tillage system (PL, NT) allows reduction of fertilization while maintaining good yields of the tested soils. Two fields (10 ha each) were established for PL and NT maize cultivation and soils (0-20 cm) were sampled two times per year–in spring (before maize sowing) and in autumn (after maize harvesting). A broad range of chemical and biological parameters (i.e. pH, forms of nitrogen, phosphorus and carbon, content of selected macronutrients and humic substances, respiration activity) were monitored during the experiment. It was evidenced that the 20% reduction in N fertilization does not have an adverse effect on the chemical and biological characteristics of soils. In turn, the maize yield was mainly the result of both the tillage system and the N rate, i.e. it was significantly higher in the PL system.

Keywords: nitrogen; reduced fertilization; maize; soil chemical and biological properties; season

1. Introduction

The current study was inspired by the latest scientific reports clearly indicating that the soil ecosystem is under threat due to over-fertilization [1–4]. It should be mentioned that the increase in the use of fertilizers on farm fields over the past 50 years has contributed to increased yields but also caused serious environmental problems. Farmers are the primary decision-makers in chemical fertilizer application [5]. Nonetheless, one of the main goals of the European Commission's "Farm to Folk" strategy to ensure a sustainable food value chain adopted recently is to reduce fertilizer use by at least 20% by 2030. The technological progress and changing climatic conditions also cause farmers to constantly seek new (optimal) agrotechnical solutions [5]. One of them is the no-till (NT) system, which combines elements of environmental protection with the improvement of economic and organizational factors on the farm [6–9] and mitigates negative climate change (less CO_2 and fumes are released into the atmosphere) [6,7]. The use of NT has increased in agricultural systems over the last 30 years [10]. In contrast to NT, many researchers have proved that conventional intensive agricultural practices (primarily excessive use of fertilizers and pesticides as well as plowing–PL system) in agricultural areas have already led to a significant decline in the quality and biodiversity of these soils [9,11–14].

Indeed, an excess of nitrogen (N) fertilizers in particular causes a reduction in the amount of plant metabolites and a decrease in the biological activity of soils. These two factors contribute to maintaining the stability of soil structure and guaranteeing its proper functioning [9,11,15]. Therefore,

 doi:10.20944/preprints202311.0125.v1

some studies have recently been focused on the reduction of chemical fertilization through the replacement thereof by bio-organic fertilizers as a solution that can limit the use of chemical fertilizers while maintaining soil fertility [16]. Fachini et al. [17] have evidenced that biochar fertilizers are an excellent alternative to traditional chemical fertilizers due to their poor solubility and minimal risk of contaminating groundwater through leaching.

The biological activity of soils, which is directly related to fertility, is largely influenced by anthropogenic activities, primarily unskillful and irrational agricultural cultivation. Thus, to obtain information about the current biological state of soils and their potential fertility, it is recommended that e.g. respiration activity (RA) [18,19] and the concentration of humic acids (HA-like) [20,21] should be measured. Respiration is a universal process carried out by all soil-dwelling heterotrophic organisms using available carbon derived from organic matter [19]. Simply, the higher the RA, the higher the abundance of living organisms in the soil environment, which is linked to the occurrence of so-called hot spots in soils [22] characterized by the greatest abundance of microorganisms and the fastest rate of metabolic processes (the most fertile areas). HA-like are organic molecules playing an essential role in improving both soil properties and plant growth [20]. Humic acids are a natural ingredient of the soil and may contribute to improved biological properties of soil. The sources of HA-like include coal, lignite, soils, and organic materials [20]. It has been evidenced that HA-like can have a positive effect on soil physical, chemical, and biological characteristics, including texture, structure, water holding capacity, cation exchange capacity, pH, carbon, enzymes, N cycling, and nutrient availability [20,21]. Consequently, the knowledge of HA-like in agricultural soils is extremely important but there are currently no studies investigating the relationship of HA-like content with reduced nitrogen fertilization, term in the vegetation season (beginning and end), and their correlation with yields, which is one of the aspects of the present paper.

Moreover, understanding and assessing the impact of reduced fertilizer application rates on soil fertility is not possible without recognizing the most important chemical characteristics of soils (e.g., pH, carbon and nutrient element content). The pH of agriculturally exploited soils is generally acidic, limiting the uptake of nutrients, which are converted into a form inaccessible to plant roots and microorganisms [4,5,13,22,23]. This usually results in a decrease in yields [9,16]. Importantly, N fertilization is well known for its impact on soil acidity in the arable layer (0-15 cm topsoil) [10,23]. Additionally, agroecosystems intensively fertilized with N may act as a source of acidifying gaseous pollutants [23]. However, it has been revealed that the reduction of chemical fertilizers combined with the use of bio-organic fertilizers prevents soil acidification and effectively improves soil chemical properties [16]. Concurrently, the carbon and nutrient contents in arable (mineral) soils are not high, which is also reflected in the quality of the soil and its crop yields [14,16,23]. Therefore, the knowledge of individual environmental parameters allows specific activities to be undertaken to reduce the adverse effects of individual factors and mitigate the worsening environmental problem (e.g. soil acidification, nutrient depletion).

In the present study, the most important chemical-physical and biological parameters were monitored before maize sowing and after harvesting. This approach facilitated the verification of the hypothesis that, in addition to the economic aspect, reduced fertilization rates combined with proper tillage systems (PL, NT) may be sufficient to maintain fertility and good quality of agriculturally exploited soils and guarantee high yields of maize.

Consequently, the main objective of the study was to check whether the 20% lower N fertilization (in agreement with the EU "Farm to Folk" directive) may ensure good yields on the one hand and, on the other hand, may contribute to maintenance of soil fertility in monoculture maize cultivation in the NT system versus the traditional PL system.

2. Materials and Methods

The field experiment was carried out in the arable fields of the Potulicka Foundation Group located in Janin (53°17′02″N 17°43′36″E) in NW Poland (kujawsko-pomorskie voivodeship).

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Two neighboring fields (10 ha each) were established for plowing (PL) and no-tillage (NT) maize cultivation. Both tillage systems had the same maize variety, sowing date, rates, and applied fertilizers and were harvested with the same combine on the same day.

The scheme of a single field with a description of the reduced fertilization pattern and rules of soil sampling is presented in Figure 1. The large-scale area of agricultural soils (20 ha) managed by the Potulicka Foundation and dedicated to the current experiment is a guarantee of the representativeness of the obtained results (taking into account the heterogeneity of the soil environment). Moreover, the Potulicka Foundation agricultural acreage is predominantly (>95%) mapped using GPS, and the precision farming system is successfully applied in the whole area [24]; hence, precise doses of fertilizers were applied and samples for analysis were collected from the same places.

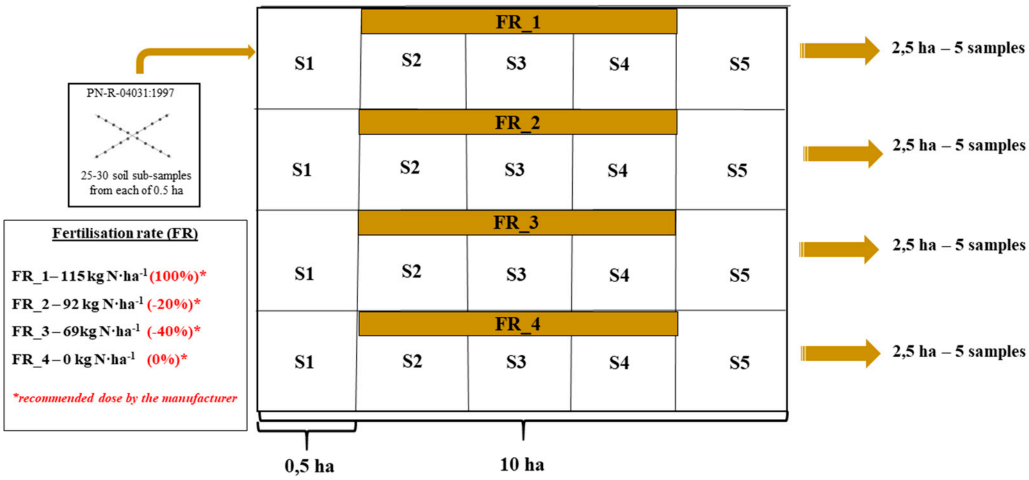

Figure 1. Scheme of the experimental field with marked fertilization rates and rules of soil sampling.

Within each of the 10 ha fields (Figure 1), 2.5-ha plots were exposed to the following N treatments: (1) control sites with no fertilization (0.0 kg ha^{-1}, FR_4) from which 5 composite samples were taken and variable N rates: (2) amount based on soil properties and crop requirements (115.0 kg ha^{-1}, FR_1) represented by 5 composite samples, (3) standard fertilizer rate reduced by 20% (in agreement with the EC directive, FR_2) represented by 5 composite samples, and (4) standard fertilizer rate reduced by 40% (also 5 composite samples, FR_3). The greatest possible representativeness of the soil material was guaranteed by the single soil sub-sampling from 25-30 randomly selected sites from each experimental "microplot" (0.5 ha area) separated from the 2.5 ha plot (Figure 1) at a surface soil depth of 0-20 cm. Finally, twenty soil samples represented the PL system, whereas another twenty samples pertained to the NT maize cultivation system.

The soil (according to the Food and Agriculture Organization of the United Nations–FAO classification: Haplic Podzol) was collected according to PN-R-04031:1997, using an automatic sampler (Wintex 100, AgroTechnology, Poland) with an Egner stick [25]. Soil samples were taken in two periods: (1) before maize sowing (April 2022) and (2) after harvesting the crop (November 2022). Importantly, pre-sowing soil samples were taken before the fertilizer application so that the freshly applied fertilizer could not disturb the tested values. The kujawsko-pomorskie voivodeship is characterized by a moderately continental climate with an average temperature of 8.7°C and rainfall of approx. 600 mm in spring and 12.2°C and approx. 400 mm in autumn. The study site represented soils classified into class V.

Phosphorus fertilization (Super FOS DAR 40™–superphosphate enriched with 40% P_2O_5) at a rate of 170 kg ha^{-1} (68 kg P_2O_5 ha^{-1}) and multi-nutrient fertilization (ICL PotashpluS™) at a rate of 150 kg ha^{-1} were applied in the studied fields. The composition of the ICL PotashpluS™ fertilizer is 37% K_2O, 9% S (24% SO_3), 3% MgO, and 8% CaO. It is worth mentioning that ICL PotashpluS™ contains boron, and 100% of sulfur, magnesium, and calcium in this fertilizer are in the form of sulfate (SO_4).

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Since 2015, the fields have remained in a monoculture of maize planted for grain (except in 2019, when maize was harvested for silage). The fertilizer reduction in the studied fields has been implemented since 2019. The maize variety grown in the experimental fields is Dekalb DKC 3730 from Bayer (Monsanto). In the studied fields, basal fertilization with urea 46% N (with urease inhibitors F.2.1) was applied at NT sowing and dosed directly by a cultivator aggregated with a seeder to a depth of about 20 cm. In the PL sowing variant, a traditional fertilizer spreader was used before tillage and the fertilizer was mixed with an approximately 5-10 cm soil layer with a cultivator. In both technologies, the doses of 0.0, 150.0, 200.0, and 250.0 kg ha^{-1} of urea corresponded to the N content of 0.0, 69.0, 92.0, and 115.0 kg N ha^{-1}.

Soil acidity (pH) was determined from a 1:2.5 soil suspension (10 g of soil, 25 mL of water) prepared in distilled water. An automatic multifunctional potential meter HQ40d equipped with a glass measuring electrode pHC301 (Hach, Loveland, CL, USA) was applied [13].

Water Holding Capacity (WHC) was determined using the under-bed (suction) method. Approximately 10-cm high plastic cylinders, onto which permeable nylon fabric membranes were placed and attached with a rubber band, were used for the measurements. The cylinders were weighed, filled with soil, and then weighed again. The determination of WHC was carried out after preparation of a cuvette. Its bottom was covered with sand at such a height that the sand covered the filler of the bottle turned upside down, thus regulating a constant water level. The cylinders of soil were placed in the cuvette prepared in this way and incubated for at least 10 days until a constant mass was obtained. After completion of the incubation, WHC was calculated using the following formulas: Mw = Mt–Ms, where, Mw is the mass of water in grams, Mt is the total mass of the container and wet soil in grams, Ms is the total mass of the container and dry soil in grams (1 g of water is equal to 1 milliliter of water, therefore, Vw = Mw). Consequently, the percentage of holding capacity (WHC%) = (Vw/Vt) × 100, where Vw is the volume of water and Vt is the total volume of saturated soil.

The total carbon (TC) content was measured using an automatic carbon analyzer TOC-V$_{CSH}$ SSM 5000 A (Shimadzu, Kyoto, Japan). 150 mg of soil was pulverized, dried, and combusted at 900°C in a column containing a platinum and cobalt oxide catalyst. All carbon compounds were converted into carbon dioxide and detected by an infrared detector [24].

Easily Degradable Carbon (EDC) was measured spectrophotometrically (λ = 550 nm, UV-1800, Shimadzu, Kyoto, Japan) in extracts prepared (2.5 g of air-dry soil sample (dw) mixed with 2 mL of 0.2 $KMnO_4$ in 1 M $CaCl_2$ (pH 7.2) and diluted to 20 mL using distilled water) according to the Weil et al. [26] method. Details are described in [22].

The content of N forms (NH_4-N and NO_3-N) and biologically available phosphorus (Olsen P) were determined colorimetrically using an AutoAnalyser 3 System (Bran+Luebbe, Norderstedt, Germany) in the prepared soil extracts (35 g of fresh soil (fw) and 100 mL of water). More methodological details are presented in our previous work [27].

The total concentrations of potassium (K), magnesium (Mg), and calcium (Ca) were established using the flame atomic absorption spectrometry (FAAS) technique (ZA-3300 Hitachi, Tokyo, Japan) after microwave mineralization of the soil material (Ethos One, Milestone, Sorisole, BG, Italy) in a mixture of HNO_3:HCl:HF (2:1:5 mL).

Total Sulfur (TS) content was determined at the District Chemical and Agricultural Station in Lublin. The determination was carried out using the nephelometric technique. The principle of the method is to oxidize organic sulfur to SO_4 and determine its content nephelometrically as BaSO4. The oxidation process while maintaining sulfur as SO_4 was carried out in an electric muffle furnace (Nabertherm) at 500°C in the presence of sodium bicarbonate and oxygen from the air. Readings were taken on a spectrophotometer capable of measuring absorbance at 490 nm (Specol 11, Carl Zeiss, Jena, Germany).

Respiration Activity (AR) in the studied soils was determined with the gas chromatography (GC) technique. Briefly, 5 g of each soil sample was placed in 60-mL dark sterile bottles, tightly closed, and incubated at 20°C for one week [27]. Both at the beginning of the experiment and after 7 days, the level of accumulated CO_2 was monitored in the headspace of the soil samples (GC CP-3800,

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Varian, Palo Alto, CL, USA). Based on the differences between the concentration of CO_2 at the start and end of the experiment, AR was calculated and expressed as the mass of produced CO_2 per the mass of fresh soil used in the experiment and per unit of time (mg CO_2 per kg of fresh soil per day).

The chemical preparation of HA-like materials was based on the Kononova and Belchikova [28] method with modifications. Briefly, the soil samples were incubated with 0.1 M NaOH in a ratio of 10 mL of liquid per g soil for 4 h with shaking at 180 rpm·min^{-1} (25°C). The supernatant was separated by centrifugation (10 min, 4000 rpm), acidified with 1 M HCl to set pH < 2, and allowed to stand overnight (HA-like precipitate). The HA-like precipitate was obtained by centrifugation at 12,000 rpm (10 min), after which it was washed with water at pH 1. The decantation process was then performed. The HA-like precipitate was stored (4°C, dark) until use. The susceptibility of the HA-like solution (0.02% HA-like, in 0.5M $NaHCO_3$ with 5% H_2O_2) precipitates to 5% H_2O_2 oxidation was determined by measuring the absorbance (at λ=465 and λ=665 nm, BioSpectrometers, Eppendorf) of the HA-like solutions [28]. The absorbance [29] was measured after 1, 6, and 24 h of oxidant treatment with simultaneous measurement of HA-like material absorbance without oxidant treatment (0.02% HA-like, in 0.5M $NaHCO_3$). The measured absorbance values and indices [29] were used as proxies for estimating the degree of humification (E4/E6). All the above-mentioned measurements were taken in triplicate. The E4/E6 ratio (ratio of the absorbances at 465 nm and at 665 nm) has been widely used to study the HA fraction [30]. The E4/E6 ratio is considered to be inversely related to the degree of condensation and aromaticity of the humic substances and to their degree of humification [31]. In our study the E4/E6 ratio was used to characterize the organic compounds in the HA-like fraction of the SOM in agricultural soil.

The yield was determined based on the weight of the harvester, previously calibrated with a legalized scale. The harvester saves a yield map; next, in the Climate FieldView™ platform [The Climate Corporation, San Francisco, USA], the selected area of the field is marked and finally a yield summary is received. The obtained data are precise because the CFV software also shows the paths of the harvester's travel, and an operator is involved during harvesting to supervise that the harvester harvests grain strictly from a given plot (in this study corresponding with the N rate) in one pass.

The data were statistically processed by means of SPSS 27 PL (IBM, Armonk, NY, USA). The requirements of parametric tests were checked using Shapiro-Wilk and Levene's statistics. In order to assess the effects of the tillage system and the level of fertilization and to compare changes over time, a MANOVA with Tukey's post hoc test was used. Then correlation analysis was conducted by calculating either Person's r or Spearman's rho coefficient, depending on data normality. A correlation matrix was prepared using R software [32]. Significance was accepted at $p < 0.05$, and all Figs present average values of the given parameter ± standard deviation (SD). For the correlation analysis, the significance of the r-values was indicated as follows: *–$p < 0.05$, **–$p < 0.01$. In order to examine the relationship between the studied soil properties and the yield obtained (after maize harvesting, Table 1), a correlation analysis was performed for the seasons separately (Figure 16, 17) and for the entire data set (Figure 18). In the description of the data, the measure of the correlation and its strength and direction are given, and statistical significance is denoted as follows: * $p < 0.05$, ** $p < 0.01$. To avoid duplication of the correlations, they are presented based on half of the matrix.

3. Results

The soil pH value in the studied fields ranged from 5.69 to 6.77 (mean 6.31±0.23), as illustrated in Figure 2. There were no statistically significant differences in the pH values between the fields depending on the farming method (pH–approx. 6.35±0.22 in the PL variant and approx. 6.28±0.24, p = 0.131 in NT). However, the analysis of the effect of reduced fertilization revealed a significant effect of the fertilizer dose on the pH in the PL field ($p < 0.001$). When comparing the first season, it was noted that the pH decreased in PL in a statistically significant manner to 6.09 only at the highest fertilizer dose, compared to the value of 6.37-6.46 in the NT variant. Taking into account three factors (tillage system, fertilizer application rate, and the two terms of the vegetation season), homogeneity in the pH of soils sampled after maize harvesting was revealed (exception: PL system with 115.0 kg of N ha^{-1}, FR_1). In turn, significant variation was observed in the soils sampled before maize sowing

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in spring, as their acidity ranged from the lowest pH (6.09) in the PL system with the application of 115.0 kg N ha^{-1} (FR_1) to the highest acidity (6.46) in the control non-fertilized soils ($p < 0.001$, Figure 2). In general, irrespective of the N dose, the acidity was by approx. 0.4 pH unit higher (close to neutral conditions) at the end of the maize vegetation season than at the start of vegetation (Figure 2).

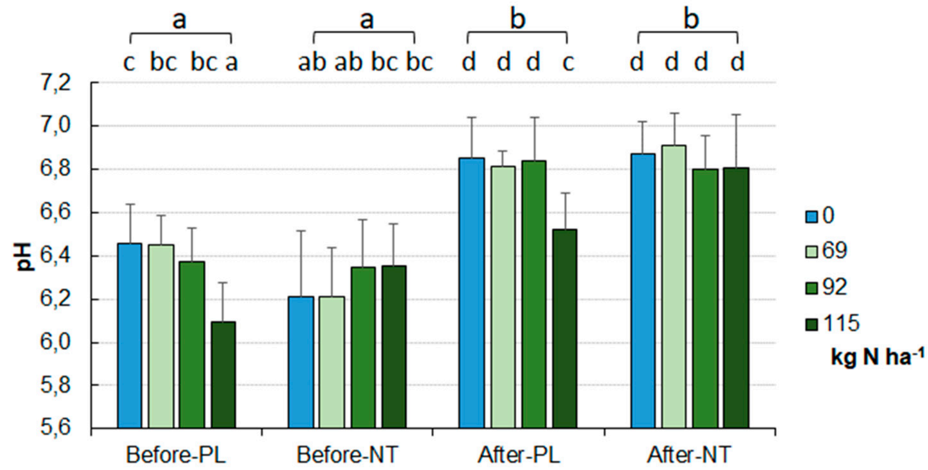

Figure 2. Variation in soil acidity in each tillage system and level of fertilization in the two terms of the vegetation season. Letters on the top of the graph show differences between both systems in time, while letters in the second row show differences between all treatments (fertilization effect in each system and time period). Values marked by the same letter do not differ between each other at α = 0.05).

A similar trend was confirmed in the WHC level (Figure 3). A significant increase in WHC from 28.21±2.51% in spring (before maize sowing) to 34.97±2.79% in autumn was recorded after maize harvesting ($p < 0.001$). In fact, this was the only factor differentiating the soils without differences within the groups (fertilizer dose) or between the tillage system (PL, NT) in a given season (before sowing, after harvesting). The lowest WHC values were recorded in spring in the PL variant (26-27%) and the highest values of the parameter were noted in autumn without the addition of fertilizer in both tillage systems of maize cultivation (36%).

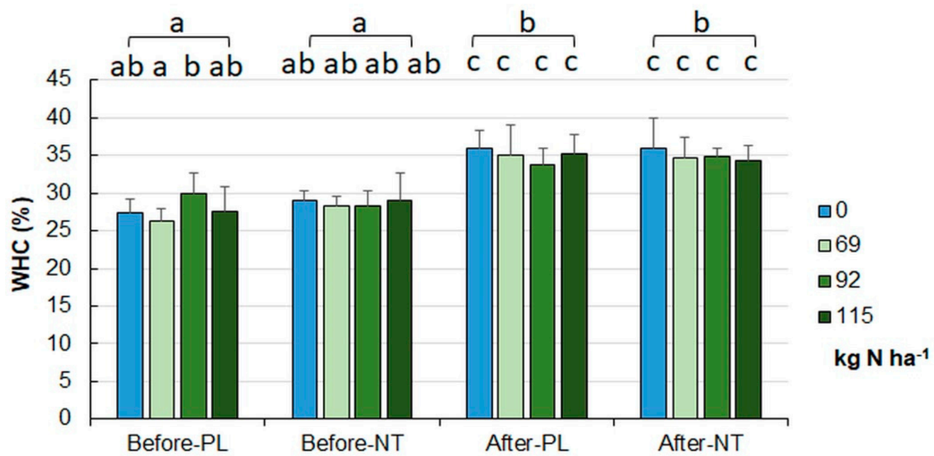

Figure 3. Variation in water holding capacity in each tillage system and level of fertilization in the two terms of the vegetation season. See the caption of Figure 2 for more details.

The analysis of the macronutrient abundance in the PL and NT fields resulted in the determination of Ca, Mg, and K levels at the beginning and end of the maize vegetation season and with reference to the fertilizer dose. The Ca content in the studied field conditions presented in Figure

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4. In spring, the soils contained an average of 95.89±57.62 mg Ca kg^{-1} dw irrespective of the tillage system and the fertilizer dose. After the maize harvest, significantly higher Ca levels were recorded, i.e. on average 869.8±477.3 mg kg^{-1} dw ($p < 0.001$). Soil samples taken from the two different tillage systems in autumn exhibited variation, with higher levels in the PL variant (c.a. 1025 mg kg^{-1} dw) than in the NT system (c.a. 713 mg kg^{-1} dw, $p < 0.001$). The analysis of the complete set-up indicated lower Ca content in the NT and 92 kg N ha^{-1} (FR_2) variant (at both the beginning and end of the maize vegetation season), and the highest content in autumn in the unfertilized part of the PL field (1224 mg kg^{-1} dw). In general, there was a trend towards the lowest Ca values in spring and the highest concentration in autumn in both the PL and NT systems ($p < 0.001$, Figure 4).

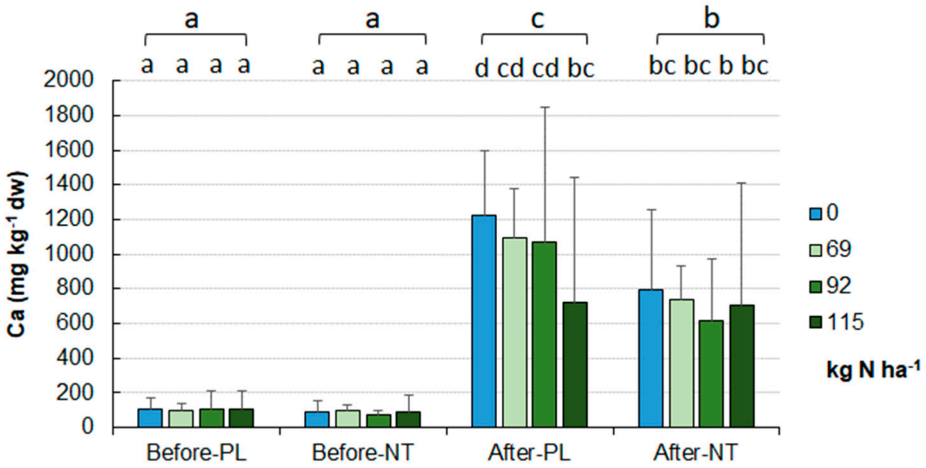

Figure 4. Changes in Ca levels in each tillage system and level of fertilization in the two terms of the vegetation season. See the caption of Figure 2 for more details.

The soil Mg level at both the beginning and end of the maize vegetation season and at the various N rates is presented in Figure 5. Similar to the content of Ca, the Mg concentration in the arable fields was significantly higher in autumn (1529.2±402.2 mg kg^{-1} dw) than in spring (711.3±235.2 mg kg^{-1} dw, $p < 0.001$). The analysis of the effect of reduced N fertilization on Mg levels both before maize sowing and after harvesting showed that the 20 and 40% fertilization reduction resulted in a slight although statistically significant decrease in the content of this element, which was particularly evident in autumn (Figure 5).

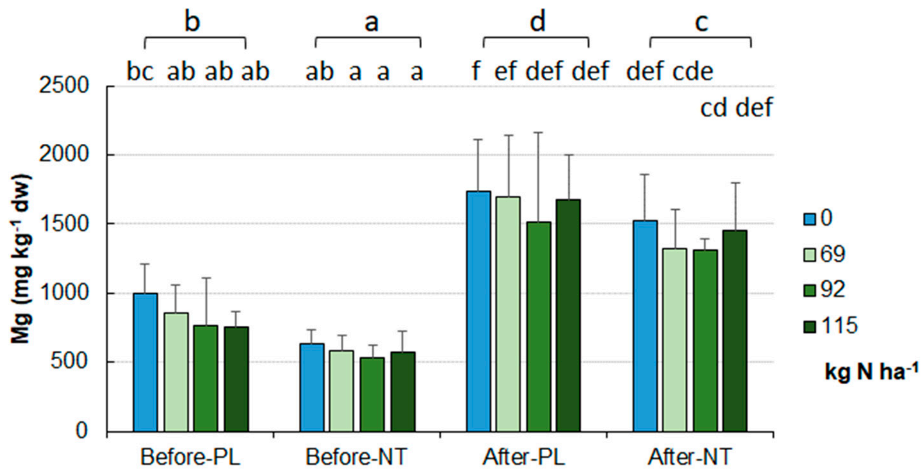

Figure 5. Changes in Mg levels in each tillage system and level of fertilization in the two terms of the vegetation season. See the caption of Figure 2 for more details.

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The K content in the maize monoculture soils exhibited a similar trend of changes to that of the elements reported above (Figure 6). From spring to autumn, the K levels increased from 10343.1±1936.9 mg kg^{-1} dw to 14623.36±1315.96 mg kg^{-1} dw ($p < 0.001$). The K content displayed variation between the seasons and tillage systems (two-factor system). The lowest values were recorded before maize sowing in NT, followed by PL, and higher values were noted after harvesting in NT and PL ($p < 0.001$). The detailed analysis revealed the lowest K content (before sowing) in the range of 8386-9438 mg kg^{-1} dw, and the highest level in the PL system and the 69.0 kg ha^{-1} N dose (FR_3) variant (16310 mg kg^{-1} dw). Summarizing, the reduction of the N fertilization dose undoubtedly does not reduce the potassium levels in soils (Figure 6).

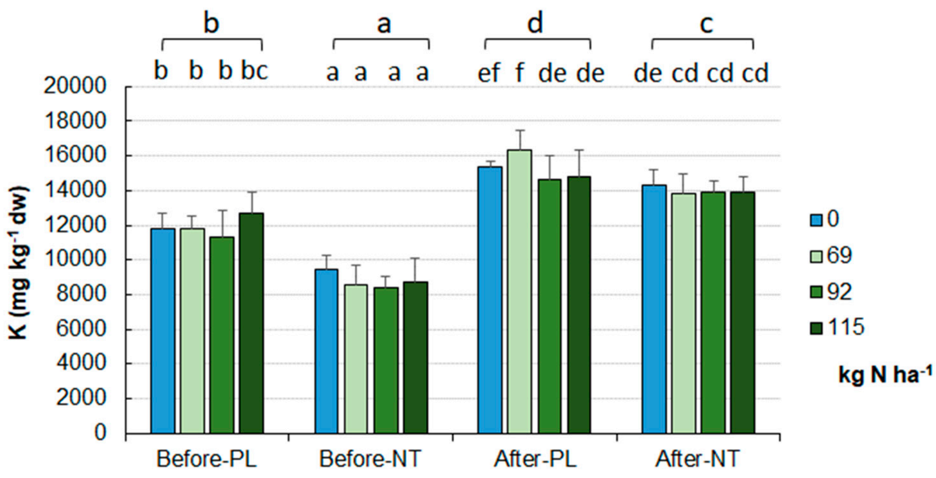

Figure 6. Changes in K levels in each tillage system and level of fertilization in the two terms of the vegetation season. See the caption of Figure 2 for more details.

The entire TC pool was constituted by total organic carbon (TOC), whose concentration did not exceed the level of 1% (due to the mineral character of the soils), with an average content of about 0.532±0.127% (Figure 7). The soils in the NT system showed statistically significantly higher TC content (mean 0.594±0.109%) than in the PL system, both collected before maize sowing (mean 0.471±0.113%, $p < 0.001$). A statistically significant effect of the fertilization level was only observed in the NT field (after harvesting), with the lowest TC content of 0.534% at 92.0 kg N ha^{-1} (FR_2) and the highest level (0.666%) at 115.0 kg N ha^{-1} (FR_1, $p < 0.01$).

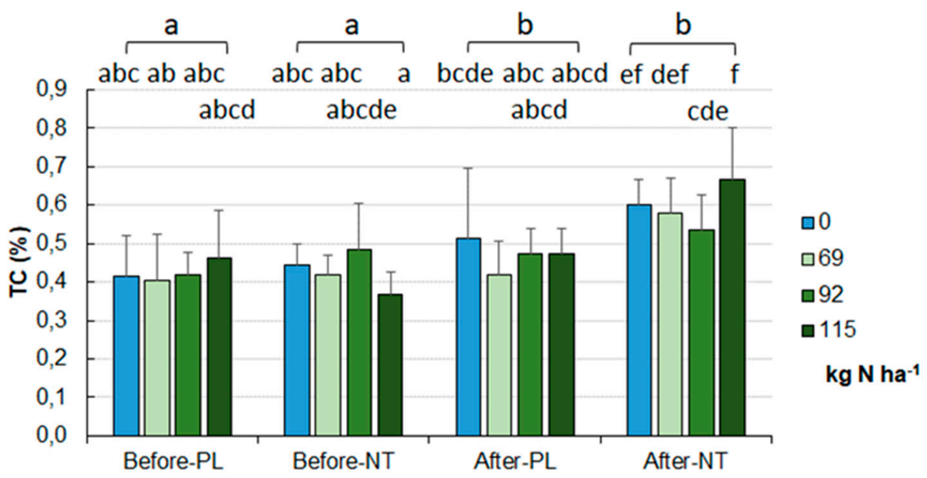

Figure 7. Changes in total carbon levels in each tillage system and level of fertilization in the two terms of the vegetation season. See the caption of Figure 2 for more details.

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To complement the data on the content of carbon in the tested soils, its bioavailable (useful) fraction for microorganisms and plants was determined (Figure 8). It was found that the EDC concentrations varied mainly between the sampling time points (before sowing and after harvesting). The pool of bioavailable carbon was significantly higher in autumn (mean 796.996±114.102 mg kg^{-1} dw) than in spring (mean 172.012±114.10 mg kg^{-1} dw, $p < 0.001$). No differences were noted between the cultivation systems in spring (170.5 and 173.5 mg kg^{-1} dw), while in autumn EDC reached maximum values in the PL system (average 832 mg kg^{-1} dw) and in NT (761.8 mg kg^{-1} dw, $p < 0.001$). It was revealed that, at the end of the growing season, the reduced fertilizer application rates did not significantly affect the level of the bioavailable form of carbon (Figure 8).

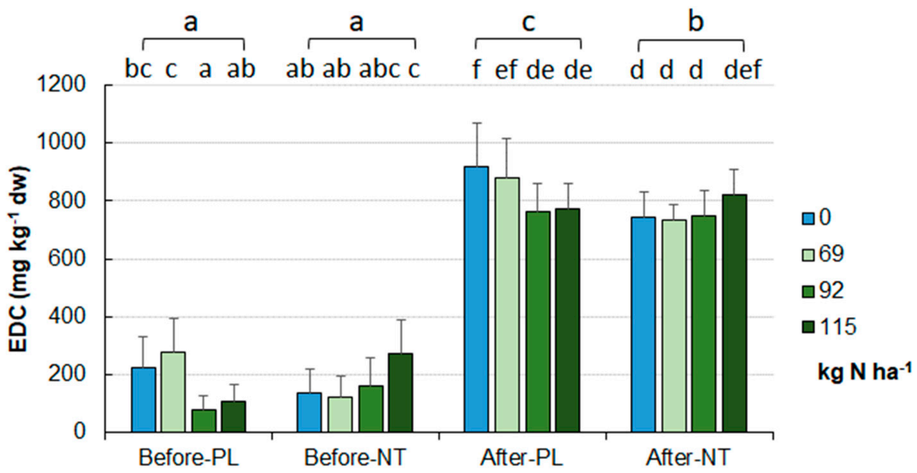

Figure 8. Changes in the easily degradable carbon pool in each tillage system and level of fertilization in the two terms of the vegetation season. See the caption of Figure 2 for more details.

As part of the comprehensive characterization of the chemical traits of the studied soils, their content of N (nitrate, ammonium) and P forms was also determined, focusing on their bioavailable (and therefore most useful) form for plants (called Olsen P). The NO_3-N (Figure 9) decreased from 5.59±2.13 mg kg^{-1} fw in spring to 1.44±1.03 mg kg^{-1} fw in autumn ($p < 0.001$). This trend was maintained at every N fertilization rate tested. The highest values of NO_3-N were recorded before maize sowing in the PL system (6.39 mg kg^{-1} fw), followed by significantly lower values in NT (4.78 mg kg^{-1} fw), whilst the lowest values were noted after harvesting ($p < 0.001$) with no significant variation between the tillage systems during this period (1.1-1.78 mg kg^{-1} fw). This trend was also confirmed by the full factorial analysis indicating the lowest nitrate values at the end of the growing season in NT with the N dose addition of 92.0 kg ha^{-1}, FR_2 (0.637 mg kg^{-1} fw), and the highest levels were recorded in PL at the beginning of vegetation with the application of 115.0 kg N ha^{-1}, FR_1 (7.42 mg kg^{-1} fw, $p < 0.001$, Figure 9).

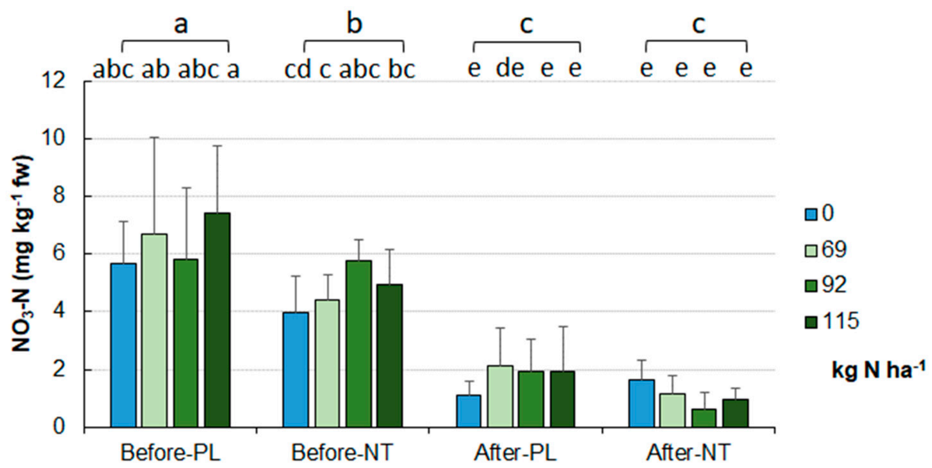

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Figure 9. Changes in the availability of nitrates (V) in each tillage system and level of fertilization in the two terms of the vegetation season. See the caption of Figure 2 for more details.

The ammonium N content increased from spring to autumn in a statistically significant manner (Figure 10) from 1.054±0.837 to 5.685±2.067 mg kg⁻¹ fw ($p < 0.001$). After harvesting the maize (in autumn), significant differences were found between the cultivation methods ($p < 0.001$), i.e. there were higher NH_4-N levels (7.038 mg kg^{-1} fw) in NT than in PL (4.33 mg kg^{-1} fw). This trend was maintained regardless of the N fertilization rate (Figure 10).

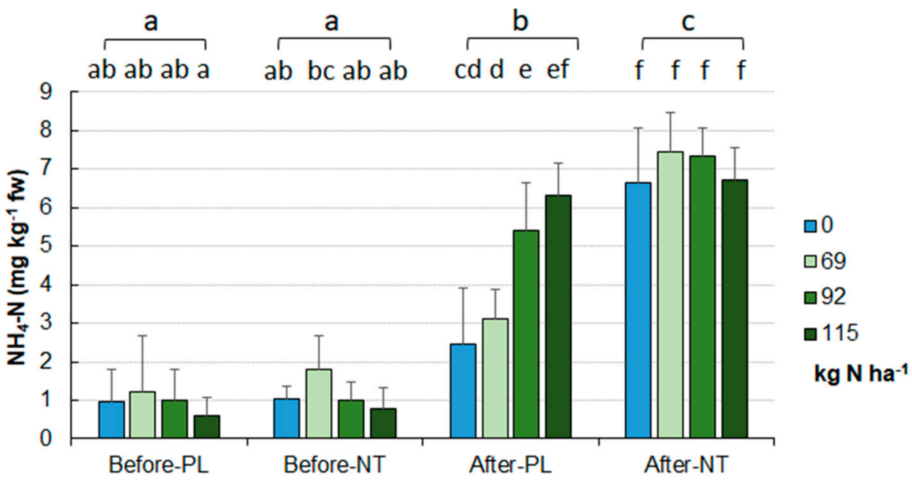

Figure 10. Changes in ammonium availability in each tillage system and level of fertilization in the two terms of the vegetation season. See the caption of Figure 2 for more details.

However, it should be noted that the 40% reduction (FR_3) of fertilization in the PL system (in autumn) resulted in a significant decrease in the soil ammonium N content in comparison to higher fertilization rates. In contrast, this relationship was not confirmed in the NT system.

After harvesting the maize crop in autumn, the pool of bioavailable Olsen P (Figure 11) increased from the initial (spring) values from 12.764±4.155 to 30.331±7.857 mg kg^{-1} fw ($p < 0.001$). Soils collected in spring differed significantly ($p < 0.001$) in the Olsen P content between the fields studied (PL, NT); however, no such differences were found between the samples collected in autumn. The analysis of all the variables revealed that there were no significant differences in soil samples exposed to the different levels of fertilization and collected before maize sowing, while samples taken after maize harvesting seemed to be more diverse in this respect ($p < 0.001$). In the PL system, the Olsen P level was significantly lower in the control soils (without fertilization) and in the low fertilization variant, while a significantly lower content of the bioavailable P was recorded at 92.0 kg N ha^{-1} (FR_2) in NT as compared to the values of other fertilization rates. At the same time, the Olsen P level was significantly higher in samples taken in autumn than in spring (Figure 11).

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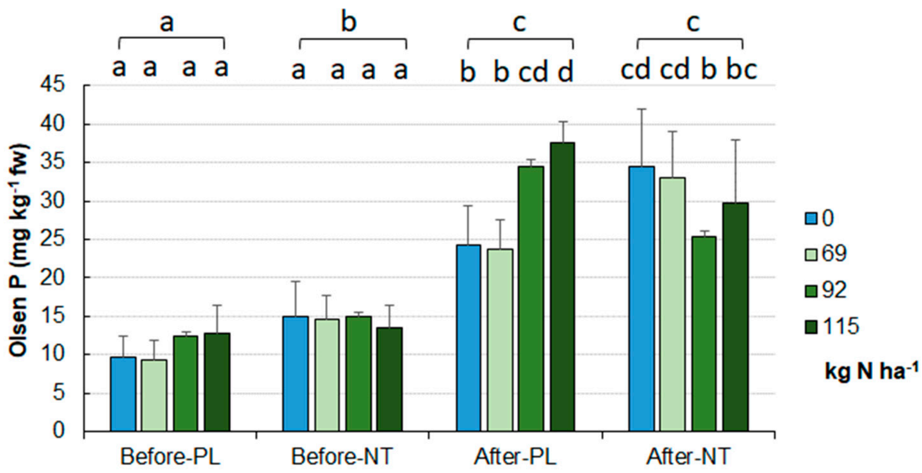

Figure 11. Changes in the availability of Olsen P in each tillage system and level of fertilization in the two terms of the vegetation season. See the caption of Figure 2 for more details.

There was also a significant increase in the TS content (Figure 12) from spring to autumn (0.009±0.001% in spring and 0.012±0.003% in autumn, $p < 0.001$) with no significant differences between the cultivation methods at each sampling date. The sulfur levels were similar in spring (0.0088-0.009%), slightly higher in autumn in the PL system (0.01-0.011%), and the highest in the NT system (0.012-0.015%, $p < 0.001$). Taking into account the N fertilization rate, it was found that the reduced N doses did not affect the TS level (Figure 12).

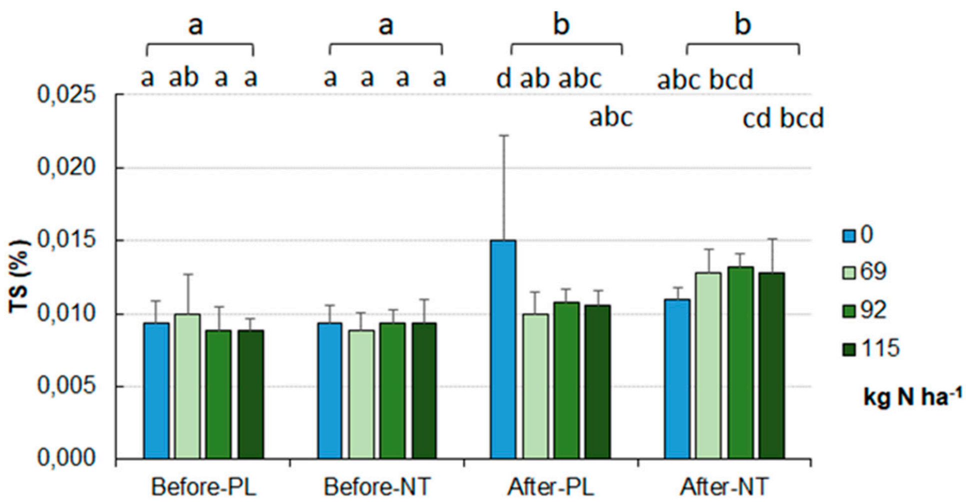

Figure 12. Changes in total sulfur levels in each tillage system and level of fertilization in the two terms of the vegetation season. See the caption of Figure 2 for more details.

The respiratory activity (AR) of the tested soils (Figure 13) was significantly higher after maize harvesting in autumn (48.9±16.7 mg CO_2 kg^{-1} fw d^{-1}) than before maize sowing in spring (20.7±7.7 mg CO_2 kg^{-1} fw d^{-1}, $p < 0.001$), showing no variation between the cropping systems in the two terms of the vegetation season. It was shown that the highest N dose recommended by the manufacturer (115.0 kg ha^{-1}, FR_1) in the PL system resulted in a decrease in AR, whereas the reduced doses (in accordance with the UE suggestion: by 20% (FR_2) and even by 40%–FR_3) had a positive impact on the level of AR. Unfortunately, this trend was insignificant (Figure 13). In the NT system, the 20% reduction in N fertilization (FR_2) was shown to have no statistically significant effect on AR.

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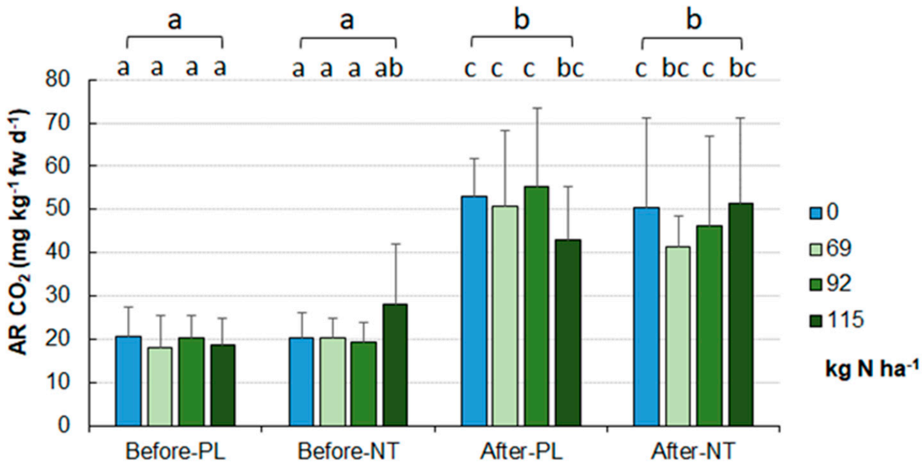

Figure 13. Changes in soil respiration activity in each tillage system and level of fertilization in the two terms of the vegetation season. See the caption of Figure 2 for more details.

The level of HA-like substances obtained in the experiment is presented in Figure 14. The content of HA-like substances was in the range of 2.37-13.66 gHA-like kg^{-1} (mean 7.69±2.42 g gHA-like kg^{-1}) and was significantly higher ($p < 0.001$) in the NT than PL system (8.79±2.11 and 6.58±.21 gHA-like kg^{-1}, respectively). The HA-like values ranged between 5.39 and 13.66 gHA-like·kg^{-1} in the NT field and between 2.37 and 11.68 gHA-like kg^{-1} in the PL system. Our results suggest that, before maize sowing in the NT, it is not necessary to apply the dose of N suggested by the manufacturer, as it resulted in a lower level of HA-like substances, whilst it is more reasonable to reduce N fertilization by 20 or even 40% at the beginning of the vegetation season, in contrast to the end of vegetation when the maximal N dose resulted in the highest content of HA-like substances in the soil.

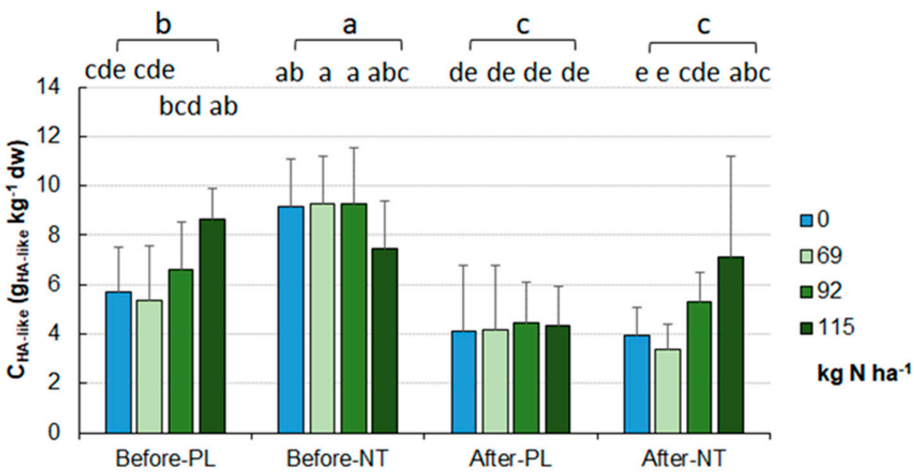

Figure 14. Changes in the content of humic acid-like substances in each tillage system and level of fertilization in the two terms of the vegetation season. See the caption of Figure 2 for more details.

The PL experimental field showed different HA-like values depending on the amount of fertilization ($p < 0.05$), i.e. the highest level of humic substances was recorded at the dose of 115.0 kg N ha^{-1} (FR_1) (8.67 gHA-like kg^{-1}) compared to the other doses (5.37-6.60 g gHA-like kg^{-1}). The analysis of the full model showed significantly lower HA-like values in the PL field at 69 kg N ha^{-1} (FR_3), while significantly higher values were recorded in the NT system with fertilization between 0.0 (FR_4) and 115.0 kg·ha^{-1} (FR_1) ($p < 0.001$) by considering all the results obtained from the two vegetation periods. The E4/E6 ratios of HA-like substances were between 0.396 and 4.880 (2.801±0.692). Significantly higher values ($p < 0.05$) were recorded for HA-like materials isolated from the PL soils (2.957±0.813, range: 0.396-4.880), while lower values were recorded for HA-like

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substances obtained from the NT soils (2.646±0.506, range: 1.727-4.000). Furthermore, significantly different E4/E6 ratios of HA-like substances were obtained in the soils treated with the different amounts of fertilization ($p < 0.001$). In the case of the HA-like substances isolated from the PL system, a significantly higher E4/E6 ratio was recorded when 69.0 kg N ha^{-1} (FR_3) was applied (3.699), while the E4/E6 ratio for the HA-like materials obtained from the NT field variant was significantly higher in the FR_4 control combination (2.961) and at 69.0 kg N ha^{-1}, FR_3 (3.091). The analysis of the full model data evidenced statistically significant differences between the E4/E6 ratios obtained from the NT at 92.0 (FR_2) and 69.0 kg N ha^{-1} (FR_3) (3.699, $p < 0.001$) (Figure 15).

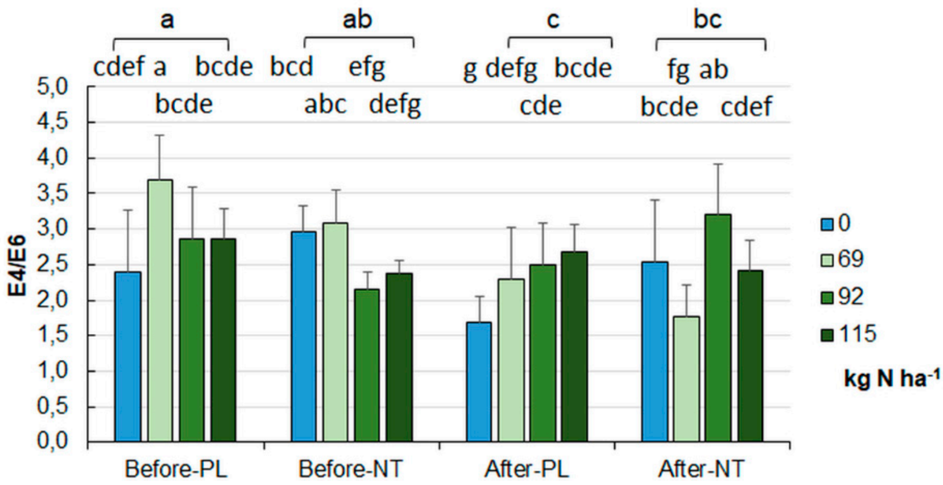

Figure 15. Changes in E4/E6 ratios in each tillage system and level of fertilization in the two terms of the vegetation season. See the caption of Figure 2 for more details.

Before maize sowing (spring, Figure 16), positive correlations were found among pH and the level of Ca, Mg, EDC, and absorbance coefficient E4/E6. In turn, negative relationships were shown between soil pH, Olsen P, and the HA-like level. At the beginning of the vegetation season, WHC correlated directly proportionally with HA-like levels, AR, and TC. The strongest positive correlations in the spring season were determined between the abundance of Mg versus Ca and K, whereas the strongest negative correlations were found between Olsen P versus Mg, K, and Ca. Equally noteworthy is the correlation between EDC and TS. After maize harvesting (autumn, Figure 17), it was also possible to determine correlations with the maize crop obtained in 2022 (Table 1).

The knowledge of the yields was available owing to the principles of precision agriculture applied on the farm of Potulicka Foundation, which made it possible to estimate that the average maize yields amounted to 4095.75 kg ha^{-1} in the PL system and 2162.05 kg ha^{-1} in the NT system (Table 2a and 2b, respectively), suggesting that the PL system is better for monoculture maize cultivation. The yield was affected by the drought phenomenon that occurred in the kujawsko-pomorskie voivodeship in 2022. Interestingly, according to the data, both fields (PL, NT) were characterized by excellent yields without additional fertilization (Table 2a, 2b). However, when the maximum fertilization rate suggested by the fertilizer supplier was assumed as 100% (FR_1), it was shown that the 20% reduction in N fertilization (FR_2) in the PL system resulted in an approximately 18% decrease in the yield, while the 40% reduction rate (FR_3) decreased the yield by approximately 6.7%. The situation was different in the case of the NT system, where the reduction of fertilization by 20% (FR_2) contributed to an approx. 20.4% increase in the maize yield versus the manufacturer's recommended rate, while the 40% reduction of the fertilization dose (FR_3) resulted in a 21.3% increase in the yield (Table 2b).

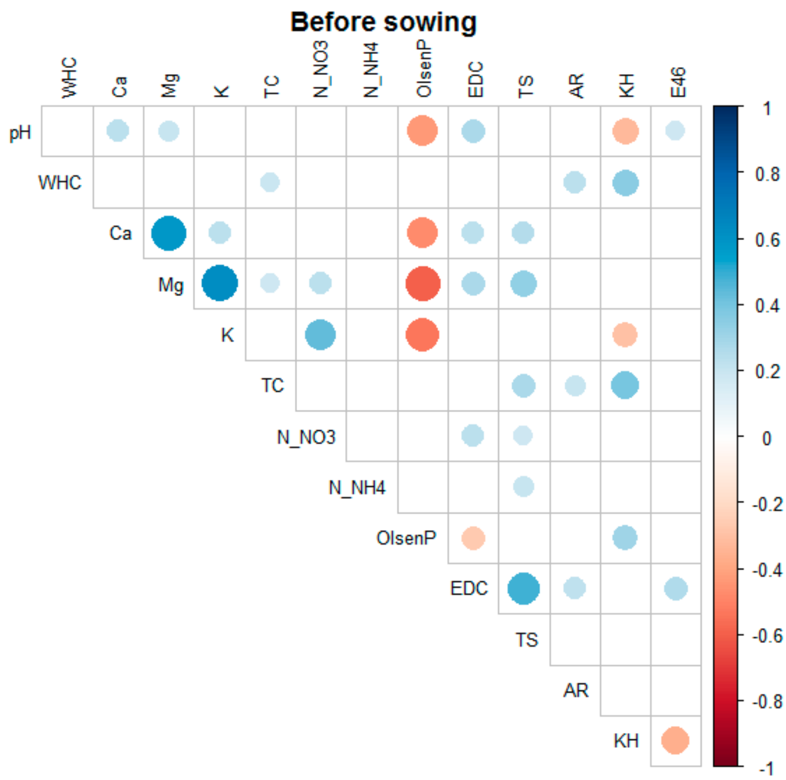

Figure 16. Correlogram between studied parameters for data collected before sowing maize.

Table 1. Correlation analysis between studied parameters and crop with Pearson r-value given with their significance (*–p < 0.05, **–p < 0.01).

	pH	WHC	Ca	Mg	K	TC	NO_3-N	NH_4-N	Olsen P	EDC	TS	AR	C_{KH}
WHC	0.127												
Ca	0.534**	0.217* 0.279**											
Mg	0.079	0.058	0.574**										
K	-0.264**	0.154	0.038	0.304**									
TC	0.036	0.164	-0.025	0.173	-0.193*								
NO_3-N	0.013	-0.039	0.304**	0.235**	0.175	-0.219*							
NH_4-N	0.058	-0.087	-0.184*	-0.269**	-0.597**	0.372**	-0.126						
Olsen P	-0.527**	-0.140	-0.559**	-0.281**	-0.104	0.015	0.022	0.221*					
EDC	0.214*	0.148	0.494**	0.502**	0.132	0.168	0.181*	-0.362**	-0.403**				
TS	0.335**	0.188*	0.064	0.136	-0.081	0.335**	-0.116	-0.023	-0.230*	0.302**			
AR	0.155	0.059	0.189*	0.240**	-0.076	0.060	0.072	-0.114	-0.039	0.251**	0.081		
C_{KH}	-0.115	-0.055	-0.238**	-0.152	-0.127	0.219*	-0.135	0.074	0.053	0.085	0.089	0.124	
Crop	0.076	0.235**	0.494**	0.740**	0.296**	0.219*	0.021	-0.138	-0.353**	0.363**	0.258**	0.061	-0.117

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Table 2. a. Average maize yield for 2022 (PL) at different nitrogen fertilization rates.

Soil raster number	Area [ha]	N dose [kg/ha]	Plot yield in the PL system [kg] wet grain	Yield per ha [kg] wet grain	Average yield for individual N rates [kg/ha] wet grain
1	0.5	0	1754	3508	
2	0.5	0	1381	2762	
3	0.5	0	3280	6560	4753.40
4	0.5	0	3081.5	6163	
5	0.5	0	2387	4774	
6	0.5	69	2502	5004	
7	0.5	69	3196.5	6393	
8	0.5	69	2702	5404	3962.20
9	0.5	69	729	1458	
10	0.5	69	776	1552	
11	0.5	92	762	1524	
12	0.5	92	941.5	1883	
13	0.5	92	1530	3060	3448.00
14	0.5	92	2911	5822	
15	0.5	92	2475.5	4951	
16	0.5	115	2559.5	5119	
17	0.5	115	2907	5814	
18	0.5	115	1799	3598	4207.40
19	0.5	115	1152.5	2305	
20	0.5	115	2100.5	4201	
					AVERAGE 4092.75

Table 2. b. Average maize yield for 2022 (NT) at different nitrogen fertilization rates.

Soil raster number	Area [ha]	N dose [kg/ha]	Plot yield in the NT system [kg] wet grain	Yield per ha [kg] wet grain	Average yield for individual N rates [kg/ha] wet grain
21	0.5	0	1629	3258	
22	0.5	0	2116	4232	
23	0.5	0	808.5	1617	2979.00
24	0.5	0	518	1036	
25	0.5	0	1921	3842	
26	0.5	69	2691	5382	
27	0.5	69	708.5	1417	
28	0.5	69	531	1062	2076.80
29	0.5	69	687.5	1375	
30	0.5	69	574	1148	
31	0.5	92	1090.5	2181	
32	0.5	92	892	1784	
33	0.5	92	696	1392	2062.20
34	0.5	92	926.5	1853	
35	0.5	92	1550.5	3101	
36	0.5	115	1463	2926	
37	0.5	115	580	1160	
38	0.5	115	500.5	1001	1712.20
39	0.5	115	689	1378	

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40	0.5	115	1048	2096	
					AVERAGE 2162.05

The correlation analysis evidenced that the maize crop was mainly affected by the content of Mg and Ca, followed by Olsen P and EDC. Other directly proportional statistically significant relationships were found for the effects of K, TS, WHC, and TC on the maize yield (Figure 17). In addition to the correlations related to the yield, after the maize harvest, the most significant relationships were noted between pH and Ca and Olsen P content. Furthermore, a significant correlation was determined between Ca and EDC and Olsen P levels. Mg was found to be significantly correlated with EDC, while K was significantly correlated with the ammonium nitrogen content (Figure 17).

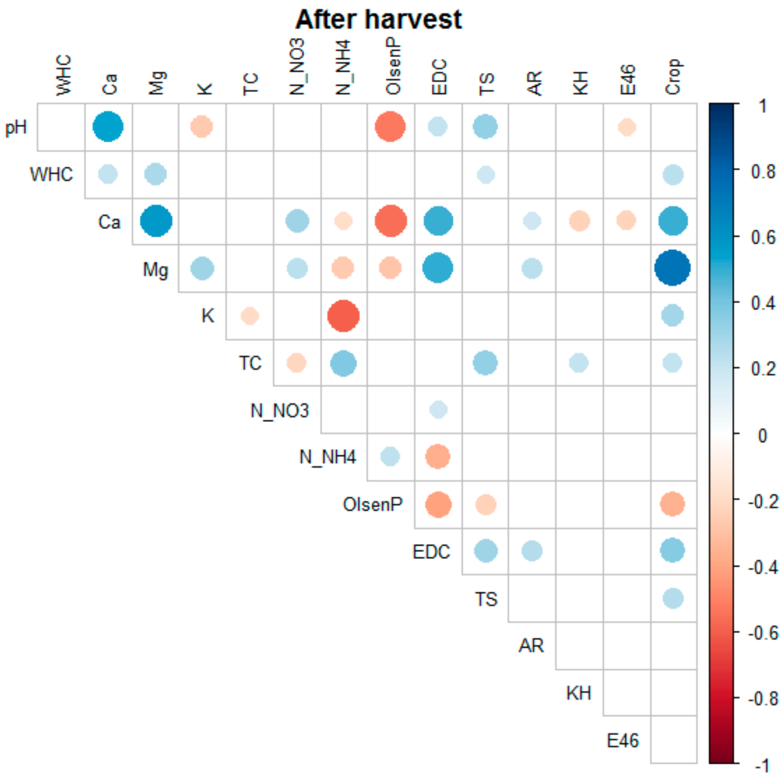

Figure 17. Correlogram between studied parameters for data collected after harvesting maize.

The compilation of the entire dataset showed numerous statistically significant correlations between the variables under study, as presented in Figure 18. It was evidenced that all the studied factors were important for maintaining good soil quality and interdependent, as confirmed by these correlations. Therefore, the factors should be constantly monitored. In general, soil pH was highly correlated with EDC, Ca, NH_4-N, Mg, NO_3-N, AR, WHC, and K and negatively correlated with the content of HA-like substances. The WHC of the studied soils was strongly positively associated with EDC, Mg, Ca, NH_4-N, AR, K, Olsen P, TS, and TC and negatively correlated with NO_3-N. The NO_3-N levels seemed to be significantly negatively correlated with EDC, Olsen P, NH_4-N, and AR. The NH_4-N content was most strongly associated with EDC, Olsen P, and AR, followed by TS, HA-like substances, and E4/E6. Olsen P was additionally correlated with EDC, AR, TS, HA-like content, and E4/E6. The EDC form of carbon was strongly dependent on AR, TS, and HA-like materials and weakly correlated with E4/E6. The total sulfur content was positively related to AR and negatively correlated with the content of humic-like substances. Finally, AR was negatively correlated with HA-like materials.

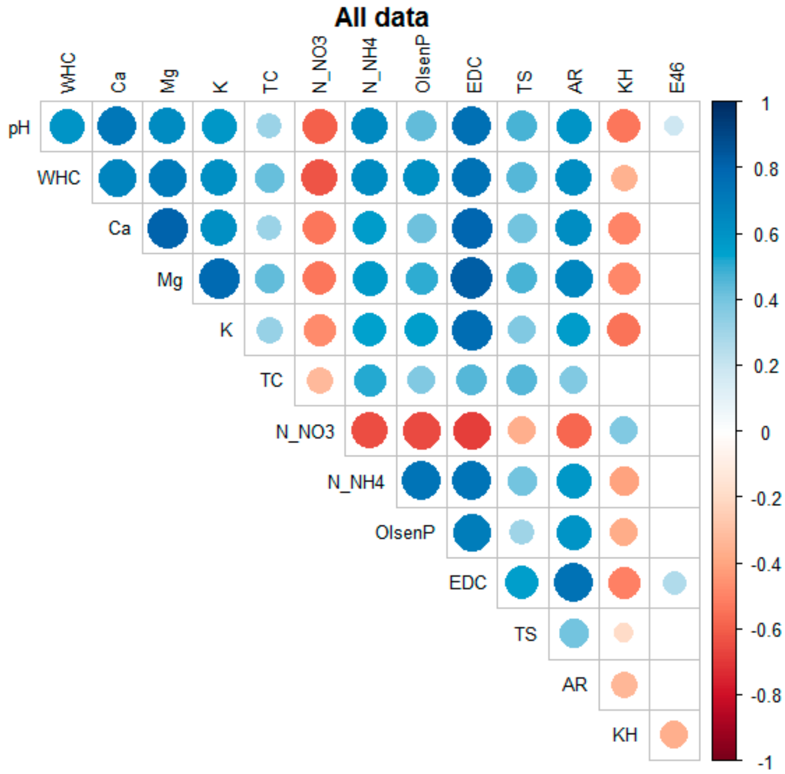

Figure 18. Correlogram between the studied parameters for the whole dataset.

4. Discussion

In this study, we intended to verify whether a reduction in N fertilization by at least 20% (in combination with the tillage system) affects the yield of maize and the chemical-physical and biological parameters of soils that guarantee their fertility. Moreover, in planning the field experiment, we went a step further from the EC recommendation (in respect to 20% fertilization reduction) and simultaneously tested a 40% reduction in N fertilization. The undoubted advantage of this study are the results achieved in a multi-area field experiment conducted by Potulicka Foundation (each field is an area of 10 hectares) rather than from small experimental plots, which incomparably improves the quality and precision of conclusions, since we worked on representative soil material, taking into account many environmental variables.

There is no doubt that fertilization is an important agricultural aspect that cannot be completely disregarded if farmers want to achieve satisfactory harvests. Optimal N management is critical for efficient crop production and agricultural pollution control [33]. However, fertilizers are often overused on smallholder farms, which not only results in lower crop yields but also causes damage to the environment and human health [33,34]. Literature data emphasize that tillage is an important management practice, with conventional tillage (CT) helping to manage weeds, prepare the soil for sowing, and mix soil nutrients and crop residues [9,35]. However, CT can also decrease soil water retention, accelerate soil erosion (given that there is minimal crop residue retained on the soil surface), increase oxidation of organic matter, and deplete N and other nutrients in soils [9]. In contrast, NT management can create a cooler microclimate in the topsoil with higher water content, i.e. more favorable for microbial growth compared to CT [9,36]. These authors studied a 48-y wheat cropping trial in semi-arid subtropical Australia with application of different tillage practices (NT and CT) and N fertilization rates (0 and 90 kg N ha^{-1}) in a Vertisol at a soil depth from 0 to 10 cm. They found that TOC significantly increased only when the N fertilizer was applied under NT. Similarly, we also noted that, in the case of maize monoculture, NT favors the presence of a higher TC pool (Figure 7). Finally, the authors concluded that NT and N fertilization exerted an important impact on soil properties and functioning over decades in Vertisol in the semi-arid subtropical region [9]. Su et al. [35], who compared crop yield data from the NT and CT systems, noted that the adoption of NT

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practice overall led to a yield decrease. This is consistent with findings reported by other researchers [36–38]. However, after one year of the experiment, we found that the differences in the maize cultivation systems resulted in higher yields in the PL vs. NT system (Table 2a, 2b). In NT, there was no plowing, which in the PL system allowed the soil to warm up faster to the depth of sowing and ensured better aeration of the soil, better preparation and, as a result, more precise sowing, which was reflected by better emergence, greater initial plant vigor, and ultimately higher yields. Nonetheless, we expect that the advantages of NT described in the literature pointed above will allow us in the long term to recommend just this system to achieve better results in maize cultivation. Yan et al. [39] have carried out a random analysis of maize yields and showed that the maize varieties and soil properties were the most important factors in the study. However, the fertilizer application rates, cultivation regions, planting systems, and soil types had weaker effects. We obtained similar results indicating differences in the yield in the maize system, which directly resulted from soil properties.

Our experiment evidenced that the combination of the three factors (time of soil sampling, cultivation system, and N dose) had an impact on soil chemical-physical and biological features. Indeed, the majority of the studied parameters (WHC, Ca, Mg, K, EDC, NH_4-N, Olsen P, TS, AR) reached higher levels after maize harvesting (autumn) than at the beginning of the vegetation season (spring) with the exception of content of NO_3-N and HA-like substances that have higher values in the spring before the maize harvest.

Our results may be supported by the findings reported by [40,41], who noted analogical differences in pH, TOC, N forms, P, K, Mg, Ca, and AR when comparing spring and autumn soil sampling. We also emphasized that, in the case of the PL cultivation system, the highest dose of N fertilization (115.0 kg ha^{-1}, FR_1) resulted in a lower pH value; therefore, when farming maize with PL, it is worth reducing the fertilization rate to prevent soil acidification. This is because of the N-fertilizer type used (urea). Furthermore, it has been shown that soil acidity drastically reduces maize crop yields and that minimum tillage has a positive effect on soil acidity [9,42]. Interestingly, in the NT system, the pH value at the highest fertilization rate was similar to that in the 20% fertilization reduction variant, which suggests that the cultivation system has a crucial role in soil acidity. It is worth mentioning here that soil acidity is accelerated by crop production practices, mainly by application of nitrogenous fertilizers to enhance crop productivity [42]. Qiao et al. [43] reported that N additions in tea plantations acidified soils (a significant decrease by 0.41 pH unit on average) and produced soil nutrient imbalance [43]. Kou et al. [44] concluded that N fertilizer reduction directly decreased the amount of NO_3-N in the soil and then alleviated the soil acidification caused by excessive use of N fertilizers. In contrast, no significant difference in TN was observed upon 25% reduction of chemical N fertilizers in the study conducted by Liu et al. [45]. It was also assumed that soil pH declined significantly when the fertilizer level exceeded 200 kg N ha^{-1} [23].

The analysis of the effect of 20% reduction of N fertilization (in accordance with the EC recommendation) showed that this amount is better for maintaining Ca levels (likewise in the case of the 40% reduction) as well as the Olsen P pool and AR levels. In recent years, studies have been conducted to determine the effects of N enrichment on AR in soil ecosystems [46,47]. However, the effect of N addition on AR remains still controversial and unclear. AR was sometimes found to increase during the first year of N fertilization but decrease in subsequent years [46,48]; hence, we decided to continue our experiment for the next vegetation season. Moreover, with respect to the TC content in the field under the NT system, it was observed that the 20% N fertilization reduction (FR_2) resulted in a lower carbon pool after the maize harvest. Due to the lack of similar studies (large-scale experiment with 20% fertilizer reduction), it is currently difficult to compare our observations with other data. However, our field experiment is being continued in the next maize vegetation season (in the same fields), which will allow verification of the present results and observed trends.

Nevertheless, it was found that the reduction in the N fertilization did not affect the level of most of the monitored parameters, e.g. WHC (no threat to the water-holding properties of soils), did not deteriorate the quality of soils in terms of Mg abundance, and did not deplete the K pool. Our study also showed that the fertilizer reduction did not have a statistically significant effect on the carbon fraction of EDCs or the nitrate abundance in the soils. Our data are compatible with the study

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conducted by Zhang et al. [9], who indicated that tillage did not have a significant effect on carbon pooling in the soil environment. The variable rates of reduced fertilization were not significantly related to the TS levels. There was also no effect of the N dose on the humic substance levels in the PL field, although a decrease in the HA-like substances was observed in the NT system after the 20 and 40% fertilization reductions, while the highest humic substance levels were recorded at the standard fertilization rate.

While analyzing the values of the E4/E6 coefficient in the two tillage systems: PL and NT and at the two terms of the vegetation season: before sowing and after harvesting the crop, it can be concluded that the HA-like substances in the soils cultivated in the NT system were characterized by a higher E4/E6 coefficient after harvesting the maize. It should be added that this correlation is not homogeneous in this cropping system, as the relationship between the land use and the degree of humic polymerization varied depending on the location of soil sampling in specific rasters. Humic acids extracted from different soils are characterized by different E4/E6 ratios. The cause of this phenomenon is the different structure of HA-like molecules and their sizes. It has been indicated that components susceptible to oxidation significantly affect the activity of soil microorganisms and thus soil fertility [29]. Moreover, E4/E6 values greater than 6 suggest the predominance of fulvic acid-type compounds, while values less than 6 point to the predominance of humic acids in the humic substance solution studied [29]. HA-like substances with higher values of this ratio characterize fertile and biologically active soils. Many authors have suggested that the value of the E4/E6 ratio, calculated for HA-like solutions, is a criterion that characterizes soil type and humus quality [29–31]. It is generally accepted that the value of this quotient is inversely proportional to the molecular weight of these compounds. As demonstrated by Watanabe et al. [49], an increase in the degree of humification with a decreasing amount of HA-like substances due to changes in land use suggests selective decomposition of humic acid molecules or parts with a low degree of humification. The higher values of the E4/E6 ratio of the HA-like substances analyzed in the soils after the maize harvest may indicate the presence of non-humidified material due to the presence of proteins and carbohydrates. Similar conclusions were made by Morán-Vieyra et al. [50], who indicated a higher value of the E4/E6 ratio in soil material from agricultural soils. The data in Figure 15 show that the E4/E6 parameter in all the studied soils had values below 6, indicating an advanced stage of humification of organic matter, with a predominance of highly polymerized humic acid-like compounds. As suggested by Licznar et al. [51], the low values of this parameter indicate the occurrence of degradation processes that are not conducive to the humification of organic matter and its transformation into high-molecular HA-like substances. Given the assumption made by Licznar et al. [51] and the values of the E4/E6 coefficient below 3 determined in the studied soils with regard to HA-like substances, it can be assumed that there are degradation processes in both fields (PL, NT), which do not support the humification of organic matter and its transformation into high molecular humus compounds. Hence, samples with a reduced E4/E6 ratio may require supplementation with humus-enhancing preparations. Importantly, an increase in the E4/E6 ratio was observed in the NT system, which may indicate the first signs of humus level restoration.

The above observations may be linked to the fact that Potulicka Foundation continuously monitors fields (precision farming) and responds to decreases or increases in individual soil parameters. The effectiveness of precision farming techniques used on the farm is also reflected in the condition of soils treated as controls (without the fertilizer), which are rich in nutrient elements. Consequently, as shown by our results, it seems reasonable to reduce N fertilization, especially since literature data proved that higher rates of N fertilization cause soil secondary salinization and acidification, and thus inhibit soil enzyme activities, functional diversity of microbial communities, and nitrification capacity [52].

5. Conclusions

The studied fields were characterized by varying values of chemical-physical and biological parameters. The time of soil sampling (before maize sowing, after maize harvesting) differentiated the values of most variables in a statistically significant way. The vast majority of the determined parameters were higher in autumn (end of the vegetation season) than in spring (beginning of the vegetation season). The following effects of reduced fertilization were evidenced:

a) in spring–a significant effect of the N dose on the increase in NO_3-N (NT), EDC (NT) and HA-like substances (PL). This was accompanied by a decrease in pH and the Mg pool (PL), a smaller pool of NH_4-N (NT) and EDC (PL), and a decrease in the E4/E6 ratio,

b) in autumn–a decrease in pH (PL), loss of Ca (both systems), NO_3-N (NT), and EDC (PL), and accumulation of NH_4-N (PL), and Olsen P (NT) with the fertilizer dose. TS decreased in NT and increased in the PL system. There was also accumulation of humic substances in the NT cultivation system.

The 20% reduction in N fertilization applied in the studied fields since 2019 does not have an adverse effect on the chemical-physical and biological characteristics of soils and the yield of maize. The results achieved after one vegetation season revealed that a 20% reduction in fertilizer application is appropriate, as it does not cause an imbalance in the most important soil parameters (reflecting fertility) or yield losses in the maize. With regard to the tillage system and maize yield, the preliminary results indicated a higher yield of maize grown as a monoculture in the PL than NT system.

Author Contributions: Conceptualization, A.W. and A.B.; methodology, A.B., A. Kr., A.S., W.G., A.Sł., A.G., and A.K.; software, A.B., and A. Sł.; validation, A.B..; formal analysis, A.B.; investigation, A.B., A.Kr., A.S., A.G., A. Sł. and A.K..; resources, A.Sł., J.P. and A.B.; data curation, A.B., A. Kr. and A.K.; writing—original draft preparation, A.W. and A.K.; writing—review and editing, A.W., A.B. and A.K.; visualization, A.B..; supervision, A.K., A.W. and A.B.; project administration, A.W. and J.P.; funding acquisition, A.W. All authors have read and agreed to the published version of the manuscript.

Funding: Scientific work supported by the state budget (Poland) under the program of the Ministry of Education and Science named "Science for the Society", project number NdS/531260/2021/2021, the amount of funding 100%, the total value of the project 625 910.50 PLN.

Data Availability Statement: Data available on request.

Conflicts of Interest: The authors declare no conflict of interest.

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