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# The Effect of Subsurface Placement of Mineral Fertilizer on Some Soil Properties under Reduced Tillage Soybean Cultivation

**Piotr Kraska , Sylwia Andruszczak *, Paweł Gierasimiuk and Hubert Rusecki**

Department of Herbology and Plant Cultivation Techniques, University of Life Sciences, Akademicka 13, 20-950 Lublin, Poland; piotr.kraska@up.lublin.pl (P.K.); pawel.gierasimiuk@interia.pl (P.G.); hubert.rusecki@gmail.com (H.R.)

* Correspondence: sylwia.andruszczak@up.lublin.pl; Tel.: +48-81-445-66-89

**Abstract:** One of the adverse effects of no-tillage is the accumulation of nutrients (in particular P and K) in the top soil layer. The subsurface application of mineral fertilizers at a depth of 10–30 cm can reduce this phenomenon and at the same time provide a relatively uniform access to soil nutrients for plant roots. Such a method of mineral fertilizer application can additionally decrease the environmental risk associated with water eutrophication because the water runoff from fields, where the soil P content is high, is reduced. The aim of this research was to evaluate the effect of the subsurface application of different rates of a compound mineral fertilizer on the content of some macronutrients, soil organic carbon content (SOC), and soil pH in a field after the harvest of soybean grown under reduced tillage conditions. The field experiment was conducted during the growing seasons of 2014/2015–2016/2017 in the village of Rogów, Zamość County, Poland. It was set up as a split-plot design in four replicates. The first experimental factor included two methods of mineral fertilization application: fertilizer broadcast over the soil surface (S); fertilizer applied deep (subsurface placed) using a specially designed cultivator (Sub-S). The other factor was the rates of the mineral fertilizer (NPKS): 85 kg·ha$^{-1}$ (F85) and 170 kg·ha$^{-1}$ (F170). Over the successive years of the study, the SOC content was found to increase. However, neither the fertilization rate nor the method of fertilizer application caused any significant difference in organic carbon. Under subsurface fertilizer application conditions, a higher soil pH was found in treatment F85, however, when the fertilizer was surface-applied, the soil in treatment F170 had a higher pH value. During the three-year study period, the P and K content in the 0–30 cm soil layer was higher than in the 30–60 cm and 60–90 cm layers. In turn, the highest Mg content was determined in the 30–60 cm layer. In the case of both mineral fertilizer application methods, a higher P content was determined in the soil fertilized at a rate of 170 kg NPKS, compared with a rate of 85 kg·ha$^{-1}$. The surface application of the higher rate of mineral fertilization resulted in an increase in the soil K content. On the other hand, when the mineral fertilizer was subsurface-applied, a higher soil K was determined in the treatments with lower mineral fertilization.

**Keywords:** soil; chemical composition; reduced tillage system; subsurface fertilization; soybean



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## 1. Introduction

In studies addressing the effects of different agronomic practices on the productivity of agroecosystems, it is of key importance to evaluate the direction of changes that occur in soil biological, chemical, and physical properties. Currently, conventional tillage with a plow dominates in Central Europe. Such tillage helps to aerate the soil, introduce crop residues, and control weeds to prepare the final seedbed. On the other hand, a traditional plow-based system can lead to many negative changes in the soil environment, such as leaching nutrients from the soil and reducing the amount of soil organic matter (SOM). In addition, the loss of SOM has a negative effect on soil structure, water capacity, and biological activity. It also increases susceptibility to water and wind erosion [1–6]. The degradation of the soil environment associated with conventional soil tillage results in a need to use new tillage technologies that will allow the biodiversity of biocenosis to be preserved, including soil conservation [7,8]. Lahmar [9] and Wauters et al. [10] report that, during the last decade, minimum/reduced tillage systems and no-tillage systems have attracted an ever-greater interest, as parts of a sustainable agriculture. Reduced cultivation is a tillage practice that does not invert the soil, combined with 30% of crop residues left on the soil surface, while no-tillage is defined as a system in which the soil remains undisturbed from harvest to planting and the seeds are drilled into the stubble of the previous crop. Compared with conventional tillage, these cultivation methods are less labor- and energy-consuming; they also beneficially affect the biological activity of soil as well as its chemical and physical properties [1–3,11,12]. It was found that no-tillage is conducive to increasing the content of organic matter in soil. Additionally, water and wind erosion are reduced, and the risk of elements being leached outside an agricultural ecosystem diminishes substantially [6,8,13–18].

The chemical properties of soil depend on the content of the elements present in the soil, the forms in which they occur, and the changes they undergo. Furthermore, the chemical properties of soil also depend on soil fauna and vegetation, human activity, as well as cropping and soil use intensity [5,7,17,19,20]. According to Wróbel and Pabin [21], changes in soil chemistry under reduced tillage conditions adversely affect nutrient supply to plants. Mineral fertilization, as one of the elements of agronomic practices, directly impacts the availability of essential nutrients in soil.

Modern agronomic technologies allow mineral fertilizers to be placed at different depths relative to the soil surface [22–25]. Lakew [26] thinks that nutrients must be supplied at an appropriate amount, form, and time in order to provide to the greatest possible extent, proper growth, and development conditions for crops. The yield-increasing effect of various nutrient application methods largely depends on soil nutrient availability and the tillage system used. The beneficial effects of subsurface fertilization are manifested more strongly under low soil disturbance conditions; hence, this fertilization method is primarily recommended in the no-tillage system [23,24,27–29].

One of the negative effects of no-tillage is the accumulation of nutrients in the top soil layer. This applies in particular to phosphorus and potassium [4,7,16,30–33]. The deep (subsurface) application of mineral fertilizers prevents P and K from accumulating in the limited soil volume and can contribute to an increased nutrient efficiency. The deep application of fertilizers, especially P-containing ones, can reduce the concentration of this element on the field surface. In this way, the environmental risks related to water erosion and the surface runoff of water, from fields in which the level of the soil P content is high, is reduced. At the same time, the deep placement of fertilizers is thought to improve the availability of nutrients contained in them, thus enhancing the effectiveness of their application [22,25,28,34–37]. Randall and Hoeft [38] give several methods of localized subsurface fertilization, notably, deep band placement, surface band placement under the seed, and band placement of fertilizer directly with the seed. Stanisławska-Glubiak and Korzeniowska [39] are of the opinion that such application of mineral fertilizers should increase the use of nutrients by plants.

This study's hypothesis was that the deep application of mineral fertilizer, compared with its surface placement, under reduced tillage conditions, would allow soybean plants to have better availability of nutrients supplied with the mineral fertilizer. Moreover, the subsurface placement of the mineral fertilizer could contribute to more even distribution of nutrients in the soil profile.

The aim of this experiment was to evaluate the effect of subsurface application of various doses of mineral fertilizer on soil pH; soil organic carbon (SOC) and the content of P, K; and Mg in the soil after the harvest of soybean grown in crop rotation (soybean—winter wheat—maize), under the conditions of reduced tillage system.

## 2. Materials and Methods

### 2.1. Study Area and Field Experiment

This study was conducted over the period 2015–2017, based on a field experiment established in the autumn of 2014 in the village of Rogów, Municipality of Grabowiec, Zamość County [50°48′22.4″ N; 23°30′00.5″ E]. The experiment was set up on brown soil (CAMBISOLS according to the World Reference Base for Soil Resources 2014) [40,41].

Before the establishment of the experiment in the autumn of 2014, soil samples were taken to determine the availability of essential elements (P, K, Mg) in the soil and its pH in the layer from 0 to 90 cm, as well as the soil organic carbon content in the 0–30 cm layer. The properties of the initial soil are given in Table 1.

**Table 1.** Properties of the initial soil of the experiment site at Rogów, in 2014.

| Initial Soil Properties | | Value |
|---|---|---|
| Soil pH | 0–30 cm soil depth | 5.01 |
| | 30–60 cm soil depth | 5.94 |
| | 60–90 cm soil depth | 6.61 |
| Available P content (mg·kg$^{-1}$) | 0–30 cm soil depth | 18.84 |
| | 30–60 cm soil depth | 10.68 |
| | 60–90 cm soil depth | 16.69 |
| Available K content (mg·kg$^{-1}$) | 0–30 cm soil depth | 78.92 |
| | 30–60 cm soil depth | 43.77 |
| | 60–90 cm soil depth | 44.51 |
| Available Mg content (mg·kg$^{-1}$) | 0–30 cm soil depth | 64.07 |
| | 30–60 cm soil depth | 69.33 |
| | 60–90 cm soil depth | 65.46 |
| SOC (g·kg$^{-1}$) | 0–30 cm soil depth | 7.9 |
| Particle size distribution | Sand (%) | 23.6 |
| | Silt (%) | 70.6 |
| | Clay (%) | 5.8 |

SOC—soil organic carbon.

The study was set up as a split-plot design. The first experimental factor included two methods of mineral fertilization application under reduced tillage conditions. In one treatment, the compound mineral fertilizer was broadcast over the soil surface (S). In the other treatment, the fertilizer was placed deep, using a specially designed cultivator, evenly at a depth of 10–30 cm of the operation of the soil loosening and fertilizer spreading attachment (S-Sub). Another factor included was the different rates of the mineral fertilizer: 85 kg NPKS·ha$^{-1}$ (F85) and 170 kg NPKS·ha$^{-1}$ (F170). In total, the experiment consisted of four treatments, each in four replicates (16 plots per year). The area of a single plot was 175 m$^2$. Between the plots with the different mineral fertilization treatments, there was a 20 m wide buffer zone necessary to properly perform specific agronomic operations.

In the experiment, the soybean cultivar, 'Annushka', was grown in crop rotation with winter wheat and maize. 'Annushka', which originated from the soybean breeding company Hodowla Soi Agroyoumis Polska, was listed in the Common Catalogue of Varieties of Agricultural Plant Species (CCA) in 2009 [42]. It is recommended for cultivation across the entire country, it is a very early variety (earliness group 0000), and its growing season lasts about 100–130 days.

Before the establishment of the experiment, winter oilseed rape was grown in the field under the condition of conventional tillage and after its harvest liming was applied by spreading chalk (CaO content 39.2%; $CaCO_3$—70%) at a rate of 5 t·ha$^{-1}$ (New Holland Tm 165 + Joskin Siroko spreader).

Soil cultivation involved disking (Terradisc 6001 T disk harrow), which was performed twice: after harvesting the previous crop and before winter. Before seed sowing, a cultivator was used (Pöttinger SYNKRO 5003 K cultivator). On the plots with surface fertilizer application, such cultivation treatment was carried out immediately after fertilizer placement (Amazone ZA TS 4200), whereas on plots with subsurface fertilizer application, the treatment was carried out during the same pass (Figure 1).

**Figure 1.** The sweep for deep mineral fertilizer application used in soybean cultivation technology.

Before sowing the soybean seeds, mineral fertilizer was applied in the form of Polifoska®6 NPK(S) 6-20-30(7), at a rate of 200 (F85) or 400 (F170) kg·ha$^{-1}$. The percentage content of all nutrients in the applied fertilizer was as follows: N—6%; $P_2O_5$—20%; $K_2O$—30%; $SO_3$—7%. In total, the mineral fertilization was the following (per hectare):

F85 = 12 kg N, 17.5 kg P, 50 kg K, 5.5 kg S (85 kg NPKS·ha$^{-1}$).

F170 = 24 kg N, 35 kg P, 100 kg K, 11 kg S (170 kg NPKS·ha$^{-1}$).

As soybean is a plant that fixes atmospheric nitrogen, no nitrogen top dressing was applied in the soybean crop. Moreover, the soybean plants were not irrigated during the growing season.

The surface placement of the fertilizer was carried out using an Amazone ZA TS 4200 spreader, whereas the subsurface application was performed using a rigid tine cultivator with its sweeps adapted to subsurface fertilizer placement. The sweeps were connected with a fertilizer hopper via a compressed air turbine, used to feed the fertilizer to the sweeps through the distribution mechanism. Moreover, this device places the fertilizer evenly at a depth of 10–30 cm of the operation of the soil loosening and fertilizer spreading attachment during one travel (Figure 1).

Cv. 'Annushka' soybeans were sown at a rate of 120 kg·ha$^{-1}$. A TERRASEM C6 seed drill was used to seed soybeans. The chemical plant protection of the soybean was as shown in Table 2.

**Table 2.** Chemical plant protection of the soybean during the growing seasons.

| Plant Protection Product | | Dose | Application Date |
|---|---|---|---|
| Seed dressing | T75 DS/WS [thiuram (a compound from the dithiocarbamate group)—750 $g \cdot kg^{-1}$] | $2 g \cdot kg^{-1}$ seeds | Before sowing |
| | Nitragina | $300 g \cdot ha^{-1}$ | Before sowing |
| Herbicide | Roundup 360 SL [glyphosate (a compound from the amino phosphonic acid group) as potassium salt—360 $g \cdot L^{-1}$]. | $1.5 L \cdot ha^{-1}$ | Before emergence |
| | Corum 502.4 SL [bentazon (a compound from the diazine group)—480 $g \cdot L^{-1}$; imazamox (a compound from the imidazolinone group)—22.4 $g \cdot L^{-1}$] | $1.25 L \cdot ha^{-1}$ | BBCH 12–25 |
| Adjuvant | Dash HC [methyl oleate—348.75 $g \cdot L^{-1}$; fatty alcohol (alkoxylated phosphoric acid ester)—209.25 $g \cdot L^{-1}$] | $1.0 L \cdot ha^{-1}$. | BBCH 12–25 |

BBCH—scale used to identify the phenological development stages of plants [43].

The soybean crop was harvested at full maturity stage using a New Holland CR 8090 combine harvester.

### 2.2. Analyses

In each year of the study, soil samples were collected for analysis after the soybean harvesting, using a modified soil auger. Soil samples were taken at 10 randomly selected sites from each experimental plot, at a soil depth of 0–30 cm, 30–60 cm, and 60–90 cm. Then, the collected soil samples were combined into one aggregate sample from each plot, separately for each soil layer. The total number of samples was 48 per year. The content of phosphorus, potassium, and magnesium, as well as the pH were determined for soil layers 0–30 cm, 30–60 cm, and 60–90 cm. The organic carbon content, in turn, was determined for a layer of 0–30 cm. The chemical analyses were carried out at the accredited laboratory, Chemical and Agricultural Station in Lublin (accreditation certificate No. AB 1186 issued by the Polish Centre for Accreditation), which meets the requirements of the PN/EN ISO/IEC 17025:2018-02 standard. The organic carbon content in the soil was determined by the Tiurin method (oxidation of soil organic carbon with excess potassium dichromate in concentrated sulphuric acid) [44], total nitrogen by the Kjeldahl method [45], available phosphorus (P) and potassium (K) by the Egner-Riehm method [46,47], available magnesium (Mg) by ASA, after the extraction of 0.0125 mole $CaCl_2 \cdot dm^{-3}$ [48], and $pH_{KCL}$ was determined potentiometrically [49].

### 2.3. Data Analysis

Analysis of variance (ANOVA) was used to statistically analyze the results by employing Statistica PL 13.3 (TIBCO Software Inc., Tulsa, OK, USA). Tukey's multiple comparison test was applied to determine the differences between the means for the main factors (methods of fertilizer application: MFA; fertilizer dose: FD; soil layer: SL; years: Y), whereas confidence intervals for the means of LSD (lowest significant difference; $p = 0.05$) were used to compare the means from the subclasses (interaction Y × SL; Y × MFA; Y × FD; MFA × SL; MFA × FD; FD × SL). The three-way interactions were not considered.

### 2.4. Characteristics of Three Growing Seasons Based on Selyaninov's Hydrothermal Coefficient

To evaluate the thermal and pluvio-thermal conditions in the three growing seasons analyzed, Selyaninov's hydrothermal coefficient was applied, following Stachowski [50], in the following form:

$$K = (P \cdot 10) / \sum t \quad (1)$$

P—sum of monthly total rainfall in mm
Σt—sum of mean daily temperatures >0 °C.

The humidity characteristics of the months and the interpretation of the hydrothermal coefficient followed Skowera and Puła [51] as well as Skowera [52], depending on the value of the coefficient k: extremely dry—k ≤ 0.4; very dry—0.4 < k ≤ 0.7; dry—0.7 < k ≤ 1.0; rather dry—1.0 < k ≤ 1.3; optimal—1.3 < k ≤ 1.6; rather humid—1.6 < k ≤ 2.0; humid—2.0 < k ≤ 2.5; very humid—2.5 < k ≤ 3.0; extremely humid—k > 3.0.

In 2015, the hydrothermal coefficient values show that water deficits occurred only in the months of June, July, and August (Table 3). The humidity index in this year demonstrates that March, April, and May were humid months.

**Table 3.** Selyaninov hydrothermal coefficients (K) during the growing seasons in the years of the experiment.

| Months | Years | | |
|---|---|---|---|
| | 2015 | 2016 | 2017 |
| March | k = 2.73 very humid | k = 4.49 extremely humid | k = 1.79 rather humid |
| April | k = 1.47 optimal | k = 2.40 humid | k = 2.66 very humid |
| Maj | k = 4.75 extremely humid | k = 1.23 rather dry | k = 1.67 rather humid |
| June | k = 0.30 extremely dry | k = 1.23 rather dry | k = 0.50 very dry |
| July | k = 0.70 very dry | k = 2.20 humid | k = 1.66 rather humid |
| August | k = 0.10 extremely dry | k = 0.94 dry | k = 0.65 very dry |
| September | k = 1.90 rather humid | k = 0.24 extremely dry | k = 2.50 very humid |
| October | k = 2.14 humid | k = 5.89 extremely humid | k = 3.97 extremely humid |
| November | k = 2.35 humid | k = 7.30 extremely humid | k = 3.11 extremely humid |

In the second year of the experiment (2016), April was a humid month that had been preceded by an extremely humid March, whereas May was a rather dry month, similarly to June.

In 2017, the humidity characteristics of the analyzed months of the growing season tended toward humid periods. Only June and August were very dry months (Selyaninov's hydrothermal coefficient was k = 0.50 and k = 0.65, respectively). During the spring and summer period, the highest rainfall was recorded in May and July, which is confirmed by Selyaninov's coefficient, according to which these months were rather humid.

## 3. Results

Given the variance analysis, the effect of years, the method of fertilizer application, the fertilizer dose, and the soil layer, as well as the interaction of these factors on pH and the content of P, K, and Mg in the soil, were significant. In contrast, no significant interactions were found between experimental factors with regard to the content of organic carbon in the soil (Table 4).

**Table 4.** Effect of years, method of fertilizer application, fertilizer dose, soil layer, and interaction of experimental factors on examined features.

| Feature | Y | MFA | FD | SL | Y × MFA | Y × FD | Y × SL | MFA × FD | MFA × SL | FD × SL |
|---|---|---|---|---|---|---|---|---|---|---|
| SOC | ** | ns | ns | – | ns | ns | – | ns | – | – |
| pH | ** | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| P | ** | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| K | ** | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| Mg | ** | ** | ** | ** | ** | ** | ** | ns | ** | ** |

Y—year; MFA—method of fertilizer application; FD—fertilizer dose; SL—soil layer; SOC—soil organic carbon [g·kg$^{-1}$]; P—content of available P [mg·kg$^{-1}$]; K—content of available K [mg·kg$^{-1}$]; Mg—content of available Mg [mg·kg$^{-1}$]; **—significant at $p = 0.05$; ns—not significant at $p = 0.05$.

The content of SOC differed significantly between the years. The highest value of SOC was found in the last year of the experiment, whereas 2015 and 2016 have similar values (Table 5). Over the three-year study period, the fertilizer application method and fertilizer rate did not significantly affect the soil organic carbon content.

**Table 5.** Soil organic carbon content in the 0–30 cm soil layer after soybean harvest (g·kg$^{-1}$).

| Method of Fertilizer Application (MFA) | Fertilizer Dose (FD) | Years (Y) | | |
|---|---|---|---|---|
| | | 2015 | 2016 | 2017 |
| S | F85 | 11.3 | 12.9 | 18.7 |
| | F170 | 10.8 | 13.2 | 18.5 |
| | Mean | 11.1 | 13.1 | 18.6 |
| Sub-S | F85 | 12.7 | 14.0 | 19.5 |
| | F170 | 11.7 | 13.2 | 22.0 |
| | Mean | 12.2 | 13.6 | 20.7 |
| Mean | F85 | 12.0 | 13.5 | 19.1 |
| | F170 | 11.3 | 13.2 | 20.3 |
| | Mean | 11.6 | 13.3 | 19.7 |
| LSD $_{0.05}$ | | | Years 4.25 | |

S—Surface fertilizer application, Sub-S—Subsurface fertilizer application; F85—fertilizer dose 85 kg NPKS·ha$^{-1}$; F170—fertilizer dose 170 kg NPKS·ha$^{-1}$; LSD $_{0.05}$—the lowest significant difference at $p = 0.05$.

The soil pH value differed significantly over the years of the study. The lowest pH was found in 2015, while the highest in the second year of the experiment (Table 6). The pH value was shown to change significantly, depending on the depth. The soil in the top 0–30 cm layer exhibited the lowest pH, whereas, with the increase in depth, the pH measured in the successive soil layers increased significantly. Treatments S were found to have a higher soil pH, compared with Sub-S. Moreover, the higher rate of mineral fertilization contributed to a significant increase in pH (Table 6).

In the soil after soybean harvest, a significant increase in the P content was found in each successive year of the study (Table 6). Furthermore, in the last year of the experiment, the soil K content was shown to significantly increase, relative to the first two years of observation. In turn, the highest Mg content was determined in 2016 (Table 6).

The content of the evaluated macronutrients in the individual soil layers differed significantly. The highest amount of P was determined in the top soil layer; it was significantly lower at the level of 60–90 cm, while it was at its lowest in the 30–60 cm layer. In the case of potassium, with the increasing depth, the content of this element significantly decreased. In turn, the highest Mg content was found in the 30–60 cm soil layer; it was significantly lower in the top 0–30 cm layer, while it was at its lowest in the 60–90 cm layer (Table 6).

**Table 6.** Evaluation of the pH and soil content of available forms of selected macronutrients after soybean harvest.

| Specification | | pH (KCl) | P (mg·kg$^{-1}$) | K (mg·kg$^{-1}$) | Mg (mg·kg$^{-1}$) |
|---|---|---|---|---|---|
| Years (Y) | 2015 | 5.74 | 13.53 | 53.73 | 68.43 |
| | 2016 | 6.23 | 15.01 | 54.17 | 71.09 |
| | 2017 | 5.89 | 16.80 | 55.02 | 69.05 |
| | LSD $_{0.05}$ | 0.006 | 0.293 | 0.673 | 0.842 |
| Soil layer (SL) | 0–30 cm | 5.32 | 19.26 | 72.53 | 69.80 |
| | 30–60 cm | 6.00 | 11.29 | 46.42 | 71.66 |
| | 60–90 cm | 6.55 | 14.79 | 43.98 | 67.11 |
| | LSD $_{0.05}$ | 0.006 | 0.293 | 0.673 | 0.842 |
| Method of fertilizer application (MFA) | S | 6.17 | 14.59 | 57.45 | 68.43 |
| | Sub-S | 5.74 | 15.64 | 51.16 | 70.62 |
| | LSD $_{0.05}$ | 0.004 | 0.199 | 0.457 | 0.572 |
| Fertilizer dose (FD) | F85 | 5.94 | 13.04 | 53.95 | 69.98 |
| | F170 | 5.97 | 17.18 | 54.67 | 69.07 |
| | LSD $_{0.05}$ | 0.004 | 0.199 | 0.457 | 0.572 |

S—Surface fertilizer application, Sub-S—Subsurface fertilizer application; F85—fertilizer dose 85 kg NPKS·ha$^{-1}$; F170—fertilizer dose 170 kg NPKS·ha$^{-1}$; LSD $_{0.05}$—the lowest significant difference at $p$ = 0.05.

In the soil sampled from the plots where the fertilizer was surface-applied (S), a significantly higher K content and, at the same time, a lower P and Mg content were found, compare to those found under deep fertilizer application conditions (Sub-S). Furthermore, it was demonstrated that the increased level of mineral fertilization promoted an increase in the soil P and K content. On the other hand, in the soil taken from the plots where the lower rate of the fertilizer Polifoska®6 had been used, a higher Mg content was determined (Table 5).

The subsurface application of mineral fertilizer, compared with S treatment, significantly decreased the soil pH in each of the evaluated soil layers (0–30 cm, 30–60 cm, and 60–90 cm) (Figure 2A). The experiment confirmed that the effect of mineral fertilizer rate on soil pH is dependent on soil depth. In the 0–30 cm and 30–60 cm layers, a higher pH was found in treatment F170, whereas, in the 60–90 cm layer, the double rate of fertilizer (F170) significantly decreased the soil pH, in comparison with treatment F85 (Figure 2B).

The highest pH was found in the plots where the higher rate of surface-applied mineral fertilization was applied (SF170) (Figure 2C).

The effect of the fertilizer application method on the soil P content was dependent on soil depth. As regards the 0–30 cm soil layer, subsurface fertilization resulted in a significant increase in the content of this element; whereas, in the 30–60 cm layer, such application of fertilizer decreased the P content, compared with the plots where the fertilizer was surface-applied. In the deepest soil layer (60–90 cm), a different method of fertilizer application did not cause any significant differences in the P content in soil (Figure 3A).

In all the soil layers evaluated, fertilization with a doubled rate of NKPS (F170) resulted in a significant increase in the P content, compared with the lower dose of 85 kg NPKS·ha$^{-1}$ (Figure 3B). The statistically proven interaction between experimental factors showed that the highest content of P in the soil was in the plot with the higher rate of mineral fertilization, applied over the soil surface (SF170) (Figure 3C).

In the 0–30 cm soil layer, the soil K content in treatment S was significantly higher, compared with SubS. A similar relationship was found for the 30–60 cm soil layer. As far as the 60–90 cm layer is concerned, the soil K concentration in treatments S and SubS was similar (Figure 4A).

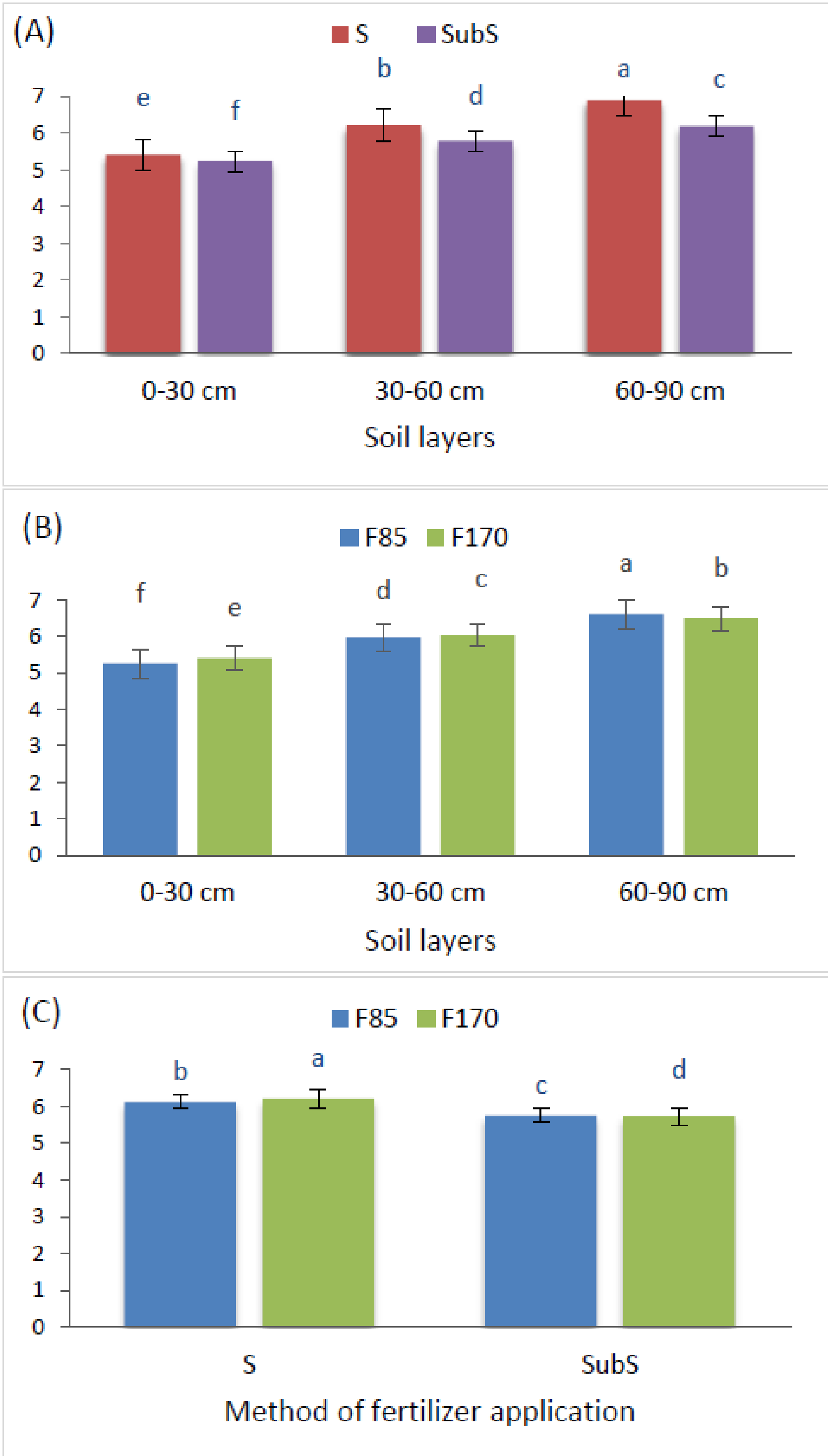


**Figure 2.** Effect of the interaction of the experimental factors on soil pH: (**A**) Method of fertilizer application × soil layer; (**B**) Fertilizer dose × soil layer; (**C**) Method of fertilizer application × fertilizer dose (S—Surface fertilizer application, SubS—Subsurface fertilizer application; F85—fertilizer dose 85 kg NPKS·ha$^{-1}$; F170—fertilizer dose 170 kg NPKS·ha$^{-1}$); different letters indicate significant differences ($p$ = 0.05).

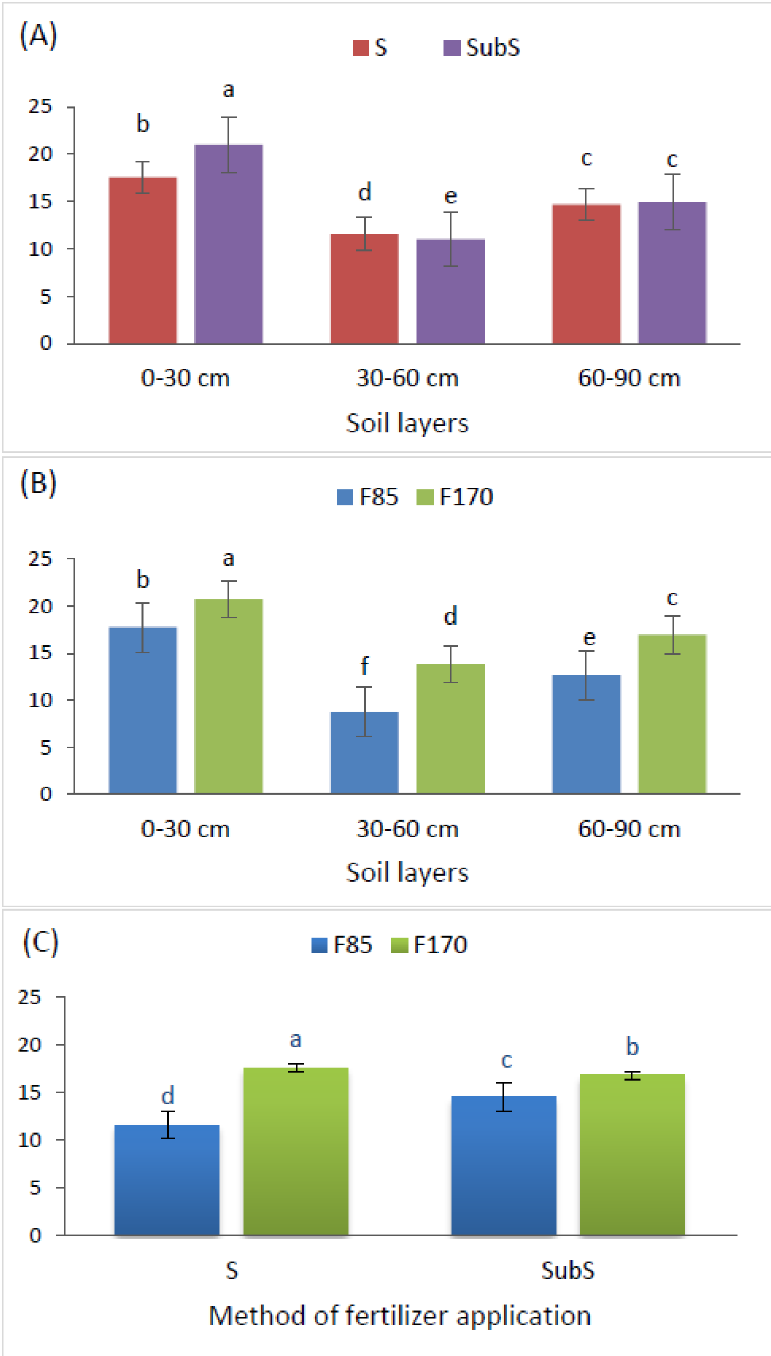


**Figure 3.** Effect of the interaction of the experimental factors on the soil content of available P [mg·kg$^{-1}$]: (**A**) Method of fertilizer application × soil layer; (**B**) Fertilizer dose × soil layer; (**C**) Method of fertilizer application × fertilizer dose (S—Surface fertilizer application, SubS—Subsurface fertilizer application; F85—fertilizer dose 85 kg NPKS·ha$^{-1}$; F170—fertilizer dose 170 kg NPKS·ha$^{-1}$); different letters indicate significant difference ($p$ = 0.05).

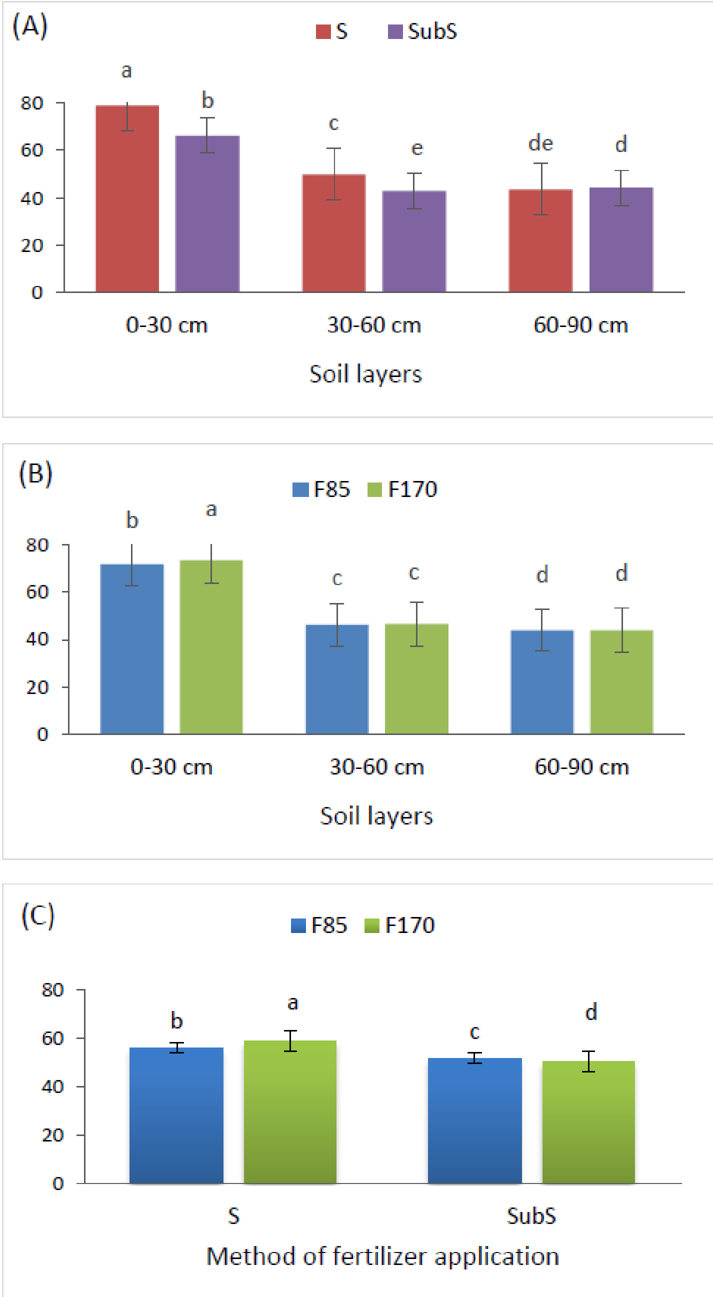


**Figure 4.** Effect of the interaction of the experimental factors on the soil content of available K [mg·kg$^{-1}$]: (**A**) Method of fertilizer application × soil layer; (**B**) Fertilizer dose × soil layer; (**C**) Method of fertilizer application × fertilizer dose (S—Surface fertilizer application, SubS—Subsurface fertilizer application; F85—fertilizer dose 85 kg NPKS·ha$^{-1}$; F170—fertilizer dose 170 kg NPKS·ha$^{-1}$); different letters indicate significant difference ($p$ = 0.05).

The proven interaction demonstrated that an increased mineral fertilization of the soybean crop significantly increased the K content in the soil only to a depth of 30 cm; whereas, in the deeper soil layers (30–60 cm and 60–90 cm), the different fertilizer rate had no impact on the K content (Figure 4B).

The surface application of the higher rate of fertilizer (SF170) resulted in an increase in the soil K content, compared with treatment F85. On the other hand, when the mineral fertilizer was subsurface-applied (SubS), a reverse relationship was found—a higher soil K content in the soil was determined in treatments F85 (Figure 4C).

The effect of the fertilizer application method on the soil Mg content was dependent on soil depth. In the 30–60 cm and 60–90 cm soil layers, a significantly higher soil Mg content was found in the treatment with subsurface fertilizer application (SubS), whereas, in the soil up to a depth of 30 cm, the Mg content did not significantly differ in both fertilization treatments (S and SubS) (Figure 5A).

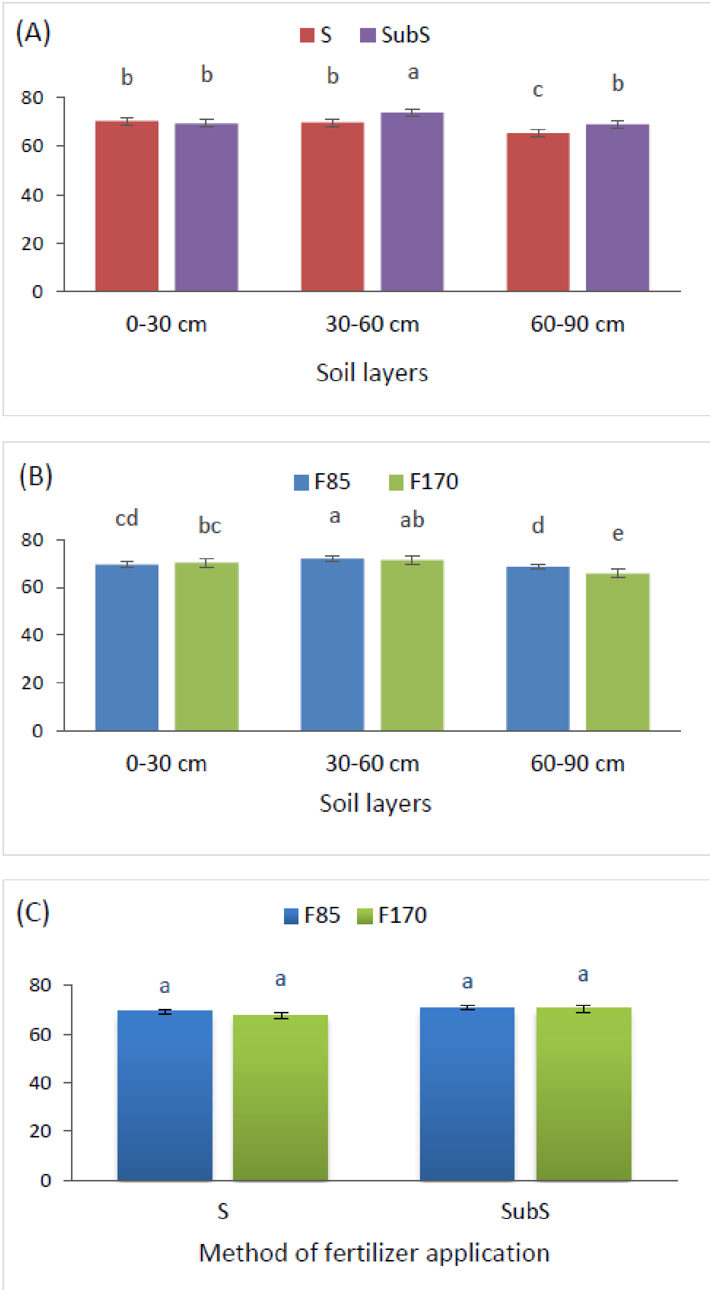


**Figure 5.** Effect of the interaction of the experimental factors on the soil content of available Mg [mg·kg$^{-1}$]: (**A**) Method of fertilizer application × soil layer; (**B**) Fertilizer dose × soil layer; (**C**) Method of fertilizer application × fertilizer dose (S—Surface fertilizer application, SubS—Subsurface fertilizer application; F85—fertilizer dose 85 kg NPKS·ha$^{-1}$; F170—fertilizer dose 170 kg NPKS·ha$^{-1}$); different letters indicate significant difference ($p$ = 0.05).

The effect of fertilizer rate on the soil Mg content depended on soil layer. Evaluating the content of this element in the 0–30 cm and 30–60 cm layers, it was found that mineral fertilization at a higher rate (170 kg NPKS) essentially did not have any statistically proven effect on its occurrence. In turn, in the 60–90 cm soil layer, a higher content of Mg was found in plots with the lower rate of mineral fertilizer (F85) (Figure 5B). The experiment did not prove a significant interaction between the fertilizer application method and fertilizer rate in relation to the soil Mg content (Figure 5C).

## 4. Discussion

In the study discussed in this paper, the soil pH in the top soil layer (0–30 cm) was lower than the one at the deeper soil levels (30–60 cm and 60–90 cm). Limousin and Tessier [53], López-Fando and Pardo [31], as well as Neugschwandtner et al. [7] also report that the non-tilled upper soil layer generally has a lower value of pH. One of the reasons for the acidification of surface soil layers under reduced tillage conditions is the accumulation of decomposition products and fertilizer substances with an acidifying effect [54]. In the study carried out by Wróbel and Pabin [21], the changes in the concentration of the main nutrients in the soil in which reduced tillage was used were accompanied by a decrease in the value of $pH_{KCl}$ in the 0–5 cm soil layer, relative to the 10–15 cm layer. Dorneles et al. [33] found a similar relationship with regard to the 5–10 cm layer. Haruna and Nkongolo [55] also obtained a lower soil pH for the 0–10 cm layer, in comparison with the soil levels of 10–20 cm, 20–40 cm, and 40–60 cm.

In the third year of the experiment, the SOC content in the top soil layer (0–30 cm) was shown to significantly increase in relation to the first and the second year of the study. It is worth noting that the value of this parameter in 2015–2017 was distinctly higher than the one determined before the establishment of the experiment (2014), by 47% in 2015 and 68% in 2016; this is while, in 2017, the value of this parameter was twice as high as in 2014. The likely cause of the increase in the soil organic carbon was the change in tillage methods: from the conventional to the reduced tillage system. Plowing, which was used in the years prior to the experiment, could accelerate the warming and drying of the soil, and thus contributed to accelerating the mineralization of organic matter and reducing its content in the soil. In turn, in our experiment, a minimum/reduced tillage without plowing was used, which was conducive to increasing the SOC content. Likewise, Alam et al. [25] found that the elimination of plowing leads to a slowed-down rate of mineralization of soil organic matter and lower soil aeration, which, in turn, promotes the greater accumulation of organic carbon in the top soil layer. Ogle et al. [56], Hermle et al. [57], Chatterjee and Lal [58], as well as Erns and Emmerling [59] found that, in non-tilled soil, the amount of the accumulated organic matter in the soil layer below 10-15 cm is lower than that in the surface layers.

Under the reduced tillage system and direct drilling, nutrients are unevenly distributed due to their greater accumulation in the top soil layer [5,7,17,55,60–62]. Under such tillage conditions, the accumulation of crop residues in the surface soil layer promotes a higher concentration of P, K, and Mg, compared with conventional tillage [7,16,31,63]. This relationship was confirmed under the conditions of the present experiment.

In the 0–30 cm and 30–60 cm soil layers, a higher potassium content was found in the treatments with the surface placement of the mineral fertilizer, compared with the deep fertilization treatment. Wróbel and Pabin [21] report that the slow movement of K deeper into the soil profile is the reason for the increased K concentration in the top soil layer under no-tillage conditions. Borges and Mallarino [37], as well as Mallarino and Borges [22] found an increased uptake of P and K by soybean under the subsurface fertilizer placement conditions. In the studies carried out by Kraska [16], as well as by Woźniak and Soroka [8], no-tillage increased the potassium content in the top soil layer. Alvarez [64], Kraska et al. [65], and Van den Putte et al. [66] also found reduced tillage to promote an increased potassium content in the soil.

Kraska et al. [65], as well as Haruna and Nkongolo [55], found that the use of reduced tillage leads to an increase in the magnesium content in the top soil layer. Włodek et al. [67], on the other hand, revealed an opposite relationship—they obtained a higher soil magnesium content in conventional tillage treatments, compared with those obtained in the reduced tillage plots. Biskupski et al. [68], in turn, did not find tillage to affect the magnesium content in the 0–40 cm soil layer. Likewise, the present study found no clear trend with regard to Mg concentration in the soil profile layers based on the method of mineral fertilizer placement under reduced tillage conditions.

According to Biskupski et al. [68], the variability in the study-results regarding the soil content of available forms of elements in different tillage systems can be due to the fact that soil can exhibit a lower temperature under reduced tillage conditions, compared with the conventional tillage conditions. This, in turn, may contribute to the slowing of chemical reactions occurring in the soil. Shen et al. [69] confirm a decrease in soil temperature under reduced tillage conditions.

The diversified level of mineral fertilizer significantly influenced the content of nutrients in the soil. The higher dose of NPKS (170 kg·ha$^{-1}$), compared with the 85 kg NPKS·ha$^{-1}$, increased the P content in all tested soil layers and increased the K content in the 0–30 cm soil layer. However, in the case of Mg, a higher dose of mineral fertilization resulted in a decrease in the content of this element in the 60–90 cm soil layer. According to Bhatt et al. [70], high doses of NPK fertilizers are required to maintain soil fertility and raise crop yields. Skowrońska [71] is of the opinion that the content of the elements in soil is primarily determined, apart from mineral fertilization, by the quantity of the yields and the uptake of nutrients from an agroecosystem.

## 5. Conclusions

The method of application and rate of mineral fertilizer did not have a significant effect on the SOC content in the top soil layer (0–30 cm). Under the deep fertilizer application conditions, the pH was lower in all the soil layers considered, in comparison with the surface fertilization treatment. The mineral fertilizer applied at the double rate (170 kg NPKS) contributed to an increase in the pH in the surface soil layer of 0–30 cm. The P and K content in the 0–30 cm soil layer was higher than the one at deeper levels of the soil profile (30–60 cm and 60–90 cm). The subsurface application of mineral fertilizer favored an increase in the content of P and Mg in the soil and a decrease in the K content, in comparison with the surface application of mineral fertilizer. The higher level of mineral fertilization promoted an increase in the soil P and K content.

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