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Article

Spatial Distribution of Soil Macroelements, Their Uptake by Plants, and Green Pea Yield under Strip-Till Technology

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Abstract: Using conservation tillage to grow crops that enhance soil quality, such as legumes, seems to be one of the best solutions for sustainable agriculture. The field study was conducted to identify the effect of soil cultivation technology and fertilization, via strip-tilling (reduced) vs. plowing (conventional), on the availability and uptake of NPK and Mg, as well as on the growth of shoots and roots and yield of green peas (*Pisum sativum* L.). The research was carried out in central Poland (53°05′16.8″ N, 19°06′14.4″ E) over two growing seasons of green peas in 2016 and 2017. Our study has shown that the spatial distribution of macroelements in the soil is influenced by the tillage method. The availability and nutrient uptake by green peas, their growth parameters, and yield were also influenced by the tillage system. However, the effect was observed mainly in the first year of the study, which had less precipitation and higher temperatures. In general, in our study, the strip-till has a positive impact on the nutrient uptake by plants, contributing to longer shoots and roots and higher biomass accumulation, especially in the first part of the growing season. In 2016, with less rainfall, green peas under strip-tilling produced more pods per plant and the yield was higher than under plowing (by 13.8%). In 2017, with higher precipitation, an increase in yield under strip-tilling compared to plowing was also observed (by 9.1%), but this difference was not statistically significant. To sum up, strip-tillage seems to have a positive impact on the spatial distribution of macroelements, growth parameters, and yield of green peas, and can be recommended as a technology for the sustainable production of this crop.

Keywords: soil layer; row; inter-row; shoots; roots; seeds; yield components

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1. Introduction

In recent years, much attention has been paid to the conservation tillage system, which has become one of the elements of sustainable agriculture [1]. Conservation tillage includes no-tillage or reduce-tillage [2]. The increasing popularity of conservation tillage may be attributed to the negative effects that conventional tillage can have on physical and biological soil properties. Conventional tillage can increase the risk of erosion, contribute to excess water loss, decrease soil organic matter, and lead to the leaching of nutrients from the soil or their direct emission into the atmosphere as greenhouse gases [3–5]. Conversely, it appears that no-till practices can have a positive impact on soil structure and biological activity, water availability, and the accumulation of organic matter in the soil, without negatively affecting plant yields [6]. One of the most important technologies included in the group of conservation cultivation is strip-tillage, which combines the positive aspect of standard plowing with no-tillage. Strip-tillage, similarly to traditional cultivation, prepares the seedbed and removes plant residues, but only in cultivation passages, which significantly reduces the expenditure (e.g., costs and energy) spent on the use of machines. On the other hand, in uncultivated strips, where plant residues remain, there is much less soil erosion, greater biological activity, better soil structure, and reduced water evaporation from the surface [7]. Moreover, since under strip-till technology fertilizers are deeply applied, there are less problems of excessive accumulation of nutrients such as P and K in the top layer of soil compared to no-till technology [4,8]. It is worth noting that strip-tillage has the advantage of releasing fewer nutrients into the atmosphere, particularly nitrogen compounds such as NO_x, N_2O, and NH_3, compared to conventional cultivation, due to the greater resources of organic matter binding macro-elements in the soil [9].

The technology of tillage and fertilization is only part of the factors influencing the availability and circulation of elements in the environment. The type of crop and its nutritional needs also play a crucial role [10]. In this aspect, legumes are very important because, thanks to symbiotic N fixation, they have a beneficial effect on the balance of this element in agroecosystems [11]. One of the most important legumes is the pea (*Pisum sativum* L.) due to its ability to grow in various weather conditions, its high yield and protein content, and its suitability to many cultivation purposes (dry or green seeds, feed and food) [12,13]. *P. sativum* has the potential to provide 50 to 80% of N necessary for its growth and development through symbiosis, leaving 60–100 kg N for subsequent plants [14,15]. Moreover, it prefers lower temperatures during the growing season and can withstand periodic frosts [16], making it suitable for cultivation in climatic conditions that are less favorable for soybeans. It is therefore a plant that should be included in field plant production, especially as a crop that allows meeting the requirements set by the EU under the common agricultural policy [17].

It seems that combining reduced tillage and soil-improving plants may be one of the best solutions that fit the idea of sustainable agriculture. Some steps have been taken to test the responses of soybeans, chickpeas, and peas for dry seeds to reduce tillage [8,18,19], but little information can be found on the reaction of green peas on such technology. The growing demand for green peas as a special food for diabetics, people with celiac disease, and vegans, or simply as food with high nutritional values [20], may result in an increase in interest in growing it as a field plant using modern cultivation systems, such as strip-tilling.

The research aimed to assess the impact of the strip-till as a reduced tillage system on the availability and uptake of the macroelements NPK and Mg by plants, as well as on the weight of shoots and roots and the yield of green peas in two growing seasons with different weather conditions.

While undertaking the research, a hypothesis was adopted: strip-tillage and deep fertilization in strip-till technology, compared to plow tillage, will result in a distribution of nutrients in the soil that is favorable for plants, which will stimulate their uptake, as well as plant growth and yield; however, this effect will depend on hydrothermal conditions during the green pea-growing season.

2. Materials and Methods

2.1. Site Description

The study was based on a field experiment located in Sokołowo, Kuyavian-Pomeranian Voivodeship, central Poland (53°05′16.8″ N, 19°06′14.4″ E) over two growing seasons of green peas in 2016 and 2017. The forecrop was winter wheat, and previously winter rapeseed was grown. The soil at the experimental sites was characterized as Luvisol (USDA). Before establishing the field experiment, soil samples were taken from the 0–20 cm soil layer, from 12 random places in the experimental field, based on which the soil properties were determined. Peas were grown on medium soil with silty loam grain size, with the following granulometric fractions: sand (2–0.05 mm) 43.5%, silt (0.05–0.002 mm) 51.1%, clay (<0.002 mm) 5.4%, and it was neutral (pH KCl 6.97). The content of available forms of macroelements in the soil was 141 mg K kg^{-1} (high), 94.5 mg Mg kg^{-1} (high), and 92.8 mg P kg^{-1} (medium). The content of organic carbon in the soil was 83.9 g C kg^{-1}, and mineral nitrogen ($N\text{-}NH_4$ + $N\text{-}NO_3$) was 6.57 mg N kg^{-1}.

2.2. Meteorological Data

Air temperature and precipitation during the green pea-growing season varied in the years of the study. In 2016, the average daily air temperatures for the subsequent pea-growing months were higher than the average temperatures in the period from April to July, 2017. The course of temperatures in the second year of the pea-growing season was more similar to the temperatures calculated for the years 1981–2010. The lowest average daily air temperature in the study years 2016 and 2017 occurred in April and amounted to 9.1 °C and 7.3 °C, respectively. The average daily temperature for the warmest month of growth, July, in the first year of cultivation was 19.2 °C, while in the next season of the study it reached 18.2 °C (Figure 1).

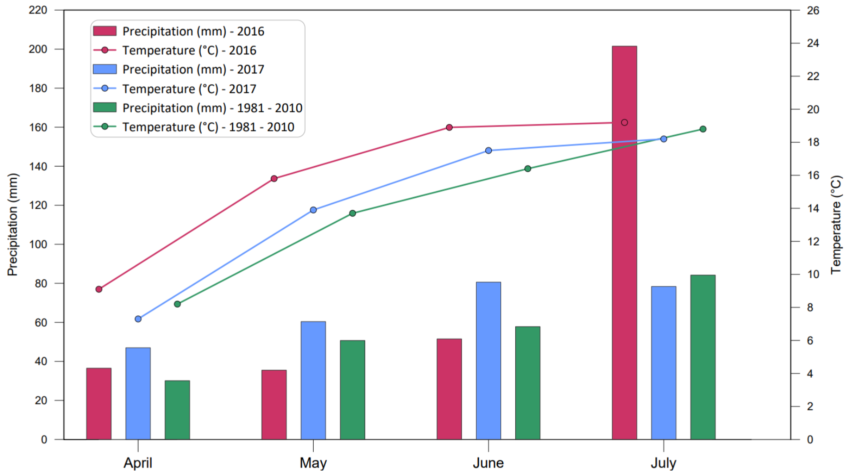

Figure 1. The weather conditions at the experimental site.

The total amount of rainfall from April to July in 2016 was 325.0 mm, and in 2017 during the same period the total amount of rainfall was 266.4 mm. In comparison, the total amount of rainfall from April to July calculated as an average for the years 1981–2010 was 222.8 mm. In 2017, in April, May, and June, during the period of emergence and the most intensive development of aboveground biomass, 188 mm of rain fell. These rainfalls were 52.2% more abundant than in the same period in 2016 and 35.6% higher than in the long-term period. July 2016 was the month of exceptionally heavy rainfall, and the total amount of rainfall during this period was 201.5 mm. These rainfalls were 123.1 mm higher than in July 2017 and 117.3 mm higher than the long-term average (Figure 1).

2.3. Experimental Treatments

The experiment was conducted in a completed randomized block design in four replications, and the plot area was 30 m^2. Two tillage systems (sowing and fertilization) were compared: moldboard plowing and strip-tilling. Under plowing (traditional tillage), deep winter plowing (25 cm) was performed in autumn (mid-November). In spring (in March), fertilizers (first dose) were applied by broadcasting with a Bogballe M2Plus spreader (Bogballe S/A, Uldum, Denmark), and after that, a drag harrow was used. Immediately before sowing, fertilizers were applied again (second dose), and a cultivation unit consisting of a disc harrow and a tube roller was used. Sowing was done with a Vaderstad Spirit 600C row seeder (Väderstad, Sweden), and row spacing was 12.5 cm. Under strip-till technology, no cultivation procedures were performed before winter. In spring, the first dose of fertilizers was applied as in the plowing system, and after two weeks, during one pass, a strip of loosened soil was prepared, and fertilizers (second dose) were applied using a Czajkowski ST cultivation and seeding unit (Czajkowski, Sokolowo, Poland). The 10–12 cm-wide and 25–30 cm-deep strip of land in which seeds are sown is also used for the deep soil application of fertilizers. The main part of the unit is the cultivation knife (farrow opener). Additional working elements are spreading and breaking discs, wavy cutting discs (up to

12 cm deep), adjustable closing and compacting discs, and the compacting and leveling roller (press rubber wheel) (Figure 2). The loosening arm is mounted between the cutting discs and the compacting discs. The Czajkowski PS seeding attachment is aggregated with the part for tillage and fertilizer application. In the attachment, seeds are sown in a 25 cm-wide strip using a chisel opener sweep. Additional elements in the attachment are a support wheel, press wheel, and post-seeding furrow. In this technology, the width of the sowing strip is 25.0 cm, and the unsown and uncultivated inter-row width is 12.5 cm.

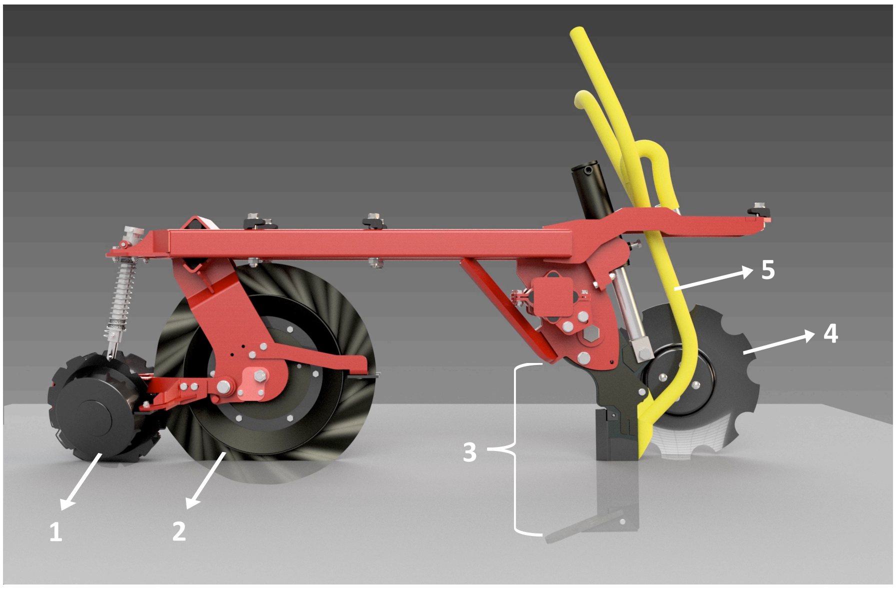

Figure 2. The strip-tillage unit (Czajkowski ST + PS) (https://czajkowski-st.com/, accessed on 15 January 2024). 1—spreading and breaking disc; 2—wavy cutting disc; 3—cultivation knife; 4—closing and compacting disc; 5—fertilizer pipe.

2.4. Agrotechnical Practices

After harvesting the previous crop (winter wheat) in mid-August, shallow (15 cm) post-harvest cultivation was carried out using a disc harrow and a tubular roller, with simultaneous sowing of a stubble catch crop [(white mustard (10 kg ha^{-1}) + sunflower (30 kg ha^{-1}) + phacelia (2 kg ha^{-1})]. The biomass of the catch crop under strip-tilling was left as mulch in spring, while under plowing it was plowed with pre-winter plowing.

At the end of March 2016 or in mid-March 2017, Kizeryt and Salmag fertilizers were broadcast over the entire field (in the plowing and strip-till system), and the rates of N, MgO, SO_3, and CaO were 41.2, 43.5, 75.0, and 5.25 kg ha^{-1}, respectively. Immediately before sowing (under plowing) or during sowing (under strip-tilling), N, P_2O_5, K_2O, MgO, and SO_3 were additionally applied at rates of 18.0, 16.5, 27.0, 4.05, and 30.0 kg ha^{-1}, as well as trace elements B, Fe, Mn, and Zn at rates of 0.022, 0.3, 0.03, and 0.03 kg ha^{-1}, respectively. Under plowing, fertilizer (Yara Mila Complex) was applied by broadcast and then mixed with the soil when sowing seeds to a depth of up to 5 cm. Under strip-tilling, in turn, fertilizer was placed deep (up to a depth of 25 cm) in the loosened sowing strip. Green peas were sown in mid-April 2016 and in the first days of April 2017, at a density of 100 pcs. m^{-2}, at a depth of 3–4 cm. Immediately after sowing, the entire field was rolled with a Crosskill-Cambridge roller. The Grundy variety seeds used were factory treated with Wakil 32.5 WG seed dressing (metalaxyl-M, fludioxonil, cymoxanil) against root rot, downy mildew, and gray mold. In order to further protect against diseases (pea powdery mildew, ascochyta blight of peas (ascochytosis)), azoxystrobin 180 g ha^{-1} and difenoconazole 112.5 g ha^{-1} (Scorpion 325 SC) were used during green pea growth. Propachizafop 60 g ha^{-1} (Agil-S 100 EC) was used to control monocotyledonous weeds, and bentazone was used to control dicotyledonous weeds, applied twice during the vegetation period, each time at 600 g ha^{-1} (Basagran 480 SL). Green peas were harvested on the first 10 days of July.

2.5. Measurements of Soil Parameters

The laser diffraction method was used to determine the soil grain size using a particle size analyzer (Malvern Instruments, Worcestershire, UK) [21]. The organic carbon content was determined using a CN elemental analyzer (Variomax CN, ELEMENTAR, Germany), following the method described by Piotrowska-Długosz et al. [22]. During the experiment, after sowing, and during the harvest of peas, soil samples were collected in three replications of each treatment, according to the procedure described in the Polish standard [23], and then subjected to chemical analysis, including determining the content of forms of phosphorus, potassium, and magnesium available to plants, as well as the content of mineral nitrogen. The soil pH was determined in a 1 M KCL solution in a soil/solution ratio of 1:2.5 potentiometrically on a pH-meter [24]. The content of phosphorus and potassium in the soil was determined by the Egner-Riehm method [25,26], and magnesium by the Schachtschabel method [27]. The content of potassium and magnesium was determined by atomic absorption spectrometry, and phosphorus by spectrophotometry. The content of nitrate nitrogen and ammonium nitrogen was determined using the flow colorimetry method [28].

2.6. Measurements of Plant Parameters

In order to determine the effect of tillage methods on the length of shoots and roots, the size of aboveground and underground biomasses, and the content of macronutrients, plant samples were collected twice during the growing period (7 and 11 weeks after sowing) from a row/strip length corresponding to an area of 0.5 m^2 (4 m under plowing and 1.33 m under strip-tilling, respectively) in four replications from each tillage system. Whole plants were collected by digging them out with a straight spade (digging at a depth of 25 cm) without separating the shoots from the roots, which made it possible to isolate individual plants. The lengths of shoots and roots were measured on 30 plants in each treatment, in four replications. Then, the entire collected shoot and root biomass (after rinsing the soil) was dried in a laboratory dryer and then ground into fractions not exceeding 0.5 cm. A laboratory sample weighing 100–200 g was taken from the sample of the entire plant biomass prepared in this way and ground again into fractions no larger than 20 µm. Then, the content of total N (Kjeldahl method [29]), P (vanadium–molybdenum method [30]), K (flame photometry method [31]), and Mg (colorimetry of titanium yellows [32]) was determined in each sample. In the collective maturity stage, samples of whole plants were taken from 1 m^2, in four replications of each treatment. In each sample, the number of pods per plant and the number of seeds per pod were determined by taking measurements on all sampled plants. Then, the seeds were shelled from the pods and weighed. The 1000-seed weight was determined by measuring twice, with 200 seeds in four replications of each treatment. The results were converted to the established seed moisture of 73%. Plant density was determined as the mean of three measurements taken during the growing season (7 and 11 weeks after sowing and just before harvesting).

2.7. Statistical Analyses

The analyzed data were described using the mean and standard deviation. The Shapiro-Wilk test was used to check the normal distribution of the variables. All of the variables were normally distributed. The collected data from our study were subjected to univariate and multivariate analysis of variance (ANOVA). One-way ANOVA was used to analyze the content and uptake of N, P, K, and Mg by green peas, their length and the dry matter weight of shoots and roots, as well as the yield and yield components of green peas. The content of minerals N, K, P, and Mg in the soil was analyzed using multivariate ANOVA. Differences between mean values were compared using Tukey's HSD (honestly significant difference) test at $p = 0.05$. All statistical calculations were carried out in the Statistica 13.0 PL statistical package (Statsoft, Cracow, Poland). A radar plot showing yield and yield components was prepared using Grapher 21 (Golden Software, Golden, CO, USA). A chart presenting the weather conditions in the growing seasons of both years of study and the average for the multiannual period was prepared in the same software.

3. Results

3.1. Content of the Macroelements in the Soil

The soil N content, measured after the sowing of green peas for both years, was influenced by the method of tillage (ST) (Figure 3A,B). On average, for soil layer (SL) and sampling place (SP) it was greater under strip-tilling compared to under plowing. There was no effect of ST on the average N content in the soil at harvest (Figure 3C,D).

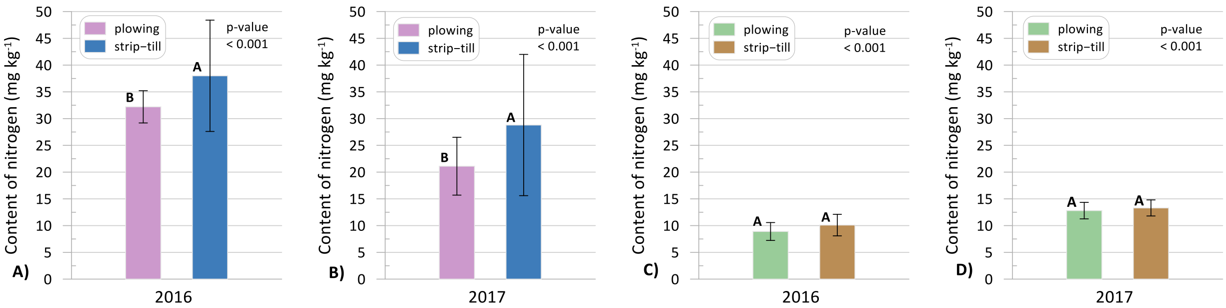

Figure 3. The content of mineral N: (**A**) 3 weeks after sowing in 2016; (**B**) 3 weeks after sowing in 2017; (**C**) at harvest in 2016; (**D**) at harvest in 2017. The values are the means for the sampling places (rows and inter-rows) and soil layers (0–20 and 20–40). A, B: the mean values with different letters are significantly different (ANOVA at the significance level $p = 0.05$).

Only in 2016, on average for SP, the 0–20 cm soil layer after sowing had a higher N content compared to the 20–40 cm layer, by 16.5% in traditional cultivation (under plowing), and 53.1% under strip-tilling (Figure 4A,B). The soil content of N, measured just before the harvest of green peas, in 2016 was also affected by the ST SL interaction. A significantly higher content of mineral N was found in the upper layer of the soil under strip-tilling than in the same layer of soil under traditional cultivation (Figure 4C).

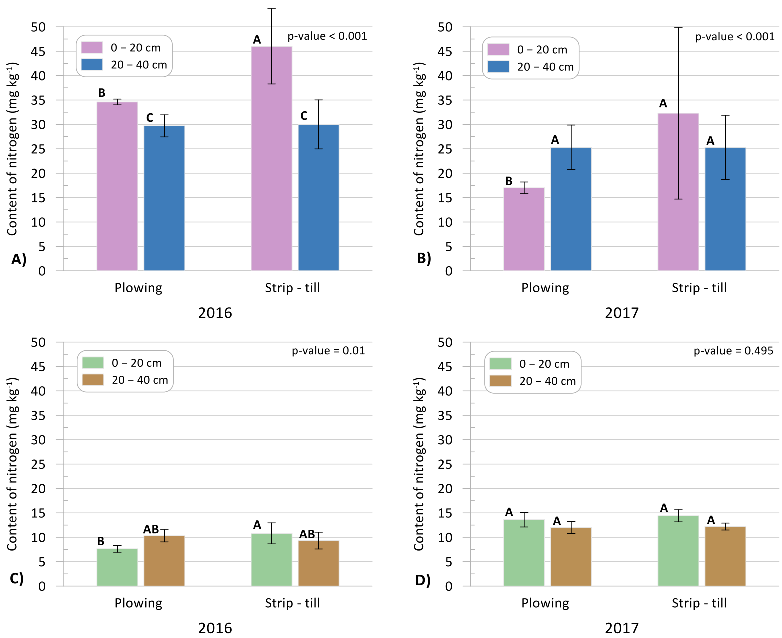

Figure 4. The content of N in soil layers 0–20 cm and 20–40 cm: (**A**) 3 weeks after sowing in 2016; (**B**) 3 weeks after sowing in 2017; (**C**) at harvest in 2016; (**D**) at harvest in 2017. The values are the means for the sampling places (rows and inter-rows). A–C: the mean values with different letters are significantly different (ANOVA at the significance level $p = 0.05$).

In each year of the study, on average for the SL, under the strip-till system, it was statistically proven that the N content after sowing was higher in the sowing strip than in inter-rows, by 31.4% and 80.5% in 2016 and 2017, respectively. In turn, under plowing, the N content in the soil in the row and inter-row was similar (Table 1).

Table 1. The content of mineral N in soil in 2016 and 2017.

Year	Soil Tillage (ST)	Soil Layer (SL)	3 Weeks after Sowing		At Harvest	
			Sampling Place (SP)			
			Row	Inter-Row	Row	Inter-Row
2016	Plowing	0–20	34.5 ^{a} ± 0.85	34.8 ^{a} ± 0.29	7.88 ^{a} ± 0.68	7.38 ^{a} ± 0.73
		20–40	29.7 ^{a} ± 2.95	29.7 ^{a} ± 6.82	10.5 ^{a} ± 1.02	9.98 ^{a} ± 1.62
		Mean	32.1 ^{B} ± 3.25	32.2 ^{B} ± 3.05	9.21 ^{A} ± 1.65	8.68 ^{A} ± 1.82
	Strip-tilling	0–20	52.8 ^{a} ± 1.85	39.2 ^{a} ± 2.42	10.7 ^{a} ± 2.80	10.9 ^{a} ± 1.91
		20–40	33.5 ^{a} ± 4.88	26.5 ^{a} ± 1.52	9.49 ^{a} ± 2.69	9.15 ^{a} ± 0.32
		Mean	43.2 ^{A} ± 11.0	32.9 ^{B} ± 7.15	11.1 ^{A} ± 2.55	10.0 ^{A} ± 1.54
p-value			ST × SP < 0.001; ST × SL × SP = 0.107		ST × SP = 0.763; ST × SL × SP = 0.874	
2017	Plowing	0–20	17.4 ^{b} ± 1.22	16.5 ^{b} ± 1.19	12.9 ^{a} ± 1.60	14.2 ^{a} ± 1.34
		20–40	24.9 ^{b} ± 5.77	25.7 ^{b} ± 4.27	11.1 ^{a} ± 0.30	12.9 ^{a} ± 1.15
		Mean	21.2 ^{B} ± 5.52	21.1 ^{B} ± 5.80	12.0 ^{A} ± 1.44	13.5 ^{A} ± 1.32
	Strip-tilling	0–20	48.2 ^{a} ± 2.76	16.2 ^{b} ± 0.84	14.5 ^{a} ± 1.85	14.3 ^{a} ± 0.64
		20–40	25.8 ^{b} ± 8.37	24.8 ^{b} ± 6.13	11.8 ^{a} ± 0.38	12.6 ^{a} ± 0.80
		Mean	37.0 ^{A} ± 13.18	20.5 ^{B} ± 6.12	13.2 ^{A} ± 1.90	13.5 ^{A} ± 1.14
p-value			ST × SP < 0.001; ST × SL × SP = 0.001		ST × SP = 0.210; ST × SL × SP = 0.819	

^{A,B}; ^{a,b}—the mean values with different letters are significantly different (ANOVA at the significance level $p = 0.05$).

The ST × SL × SP interaction indicates that in 2017, after sowing, the highest soil N content was in the upper soil layer (0–20 cm) under strip-tilling. Under plowing, in no year of the study were there any differences in the N content in 0–20 and 20–40 cm soil layers, sampled in rows or inter-rows (Table 1).

No differences were found between the methods of tillage in the soil K content 3 weeks after the sowing of green peas, on average for SL and SP in 2016 and 2017 (Figure 5A,B). The analysis of K concentration in the soil just before the crop harvest indicates a significant impact of the tillage system in 2017, in which the amount of this component was greater under strip-tilling compared to plowing (Figure 5D).

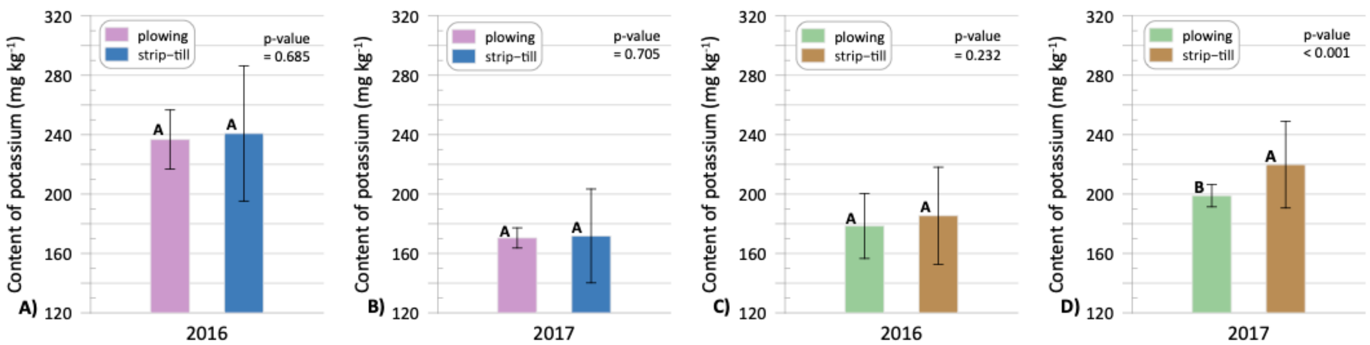

Figure 5. The content of available K: (**A**) 3 weeks after sowing in 2016; (**B**) 3 weeks after sowing in 2017; (**C**) at harvest in 2016; (**D**) at harvest in 2017. The values are the means for the sampling places (rows and inter-rows) and soil layers (0–20 and 20–40). A, B: the mean values with different letters are significantly different (ANOVA at the significance level $p = 0.05$).

For both years, K content was affected by the ST × SL interaction. After sowing green peas under strip-tilling, a higher K content was found in the 0–20 cm soil layer compared to the 20–40 cm layer, by 30.3% and 38.4% in 2016 and 2017, respectively (Figure 6A,B). Moreover, in 2017, the upper soil layer (0–20 cm) was characterized by a significantly higher K content under strip-tilling compared to the soil from both layers of the analyzed profile under traditional cultivation. Under the plowing system, in no year of the study were there any differences in K content in the soil after sowing between the 0–20 and 20–40 cm layers.

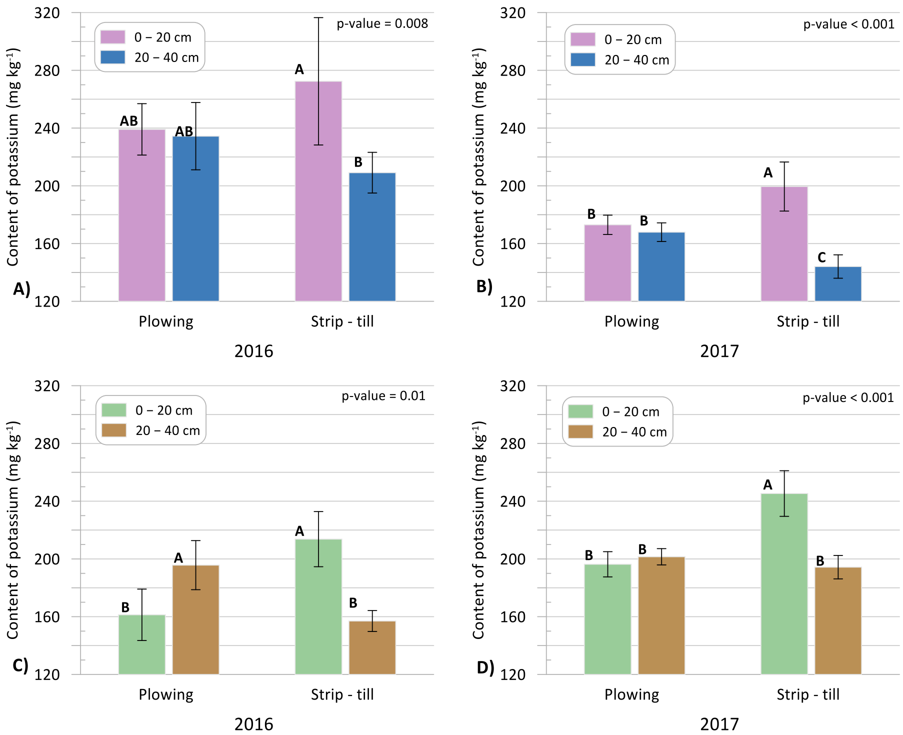

Figure 6. The content of available K in soil layers 0–20 cm and 20–40 cm: (**A**) 3 weeks after sowing in 2016; (**B**) 3 weeks after sowing in 2017; (**C**) at harvest in 2016; (**D**) at harvest in 2017. The values are the means for the sampling places (rows and inter-rows). A–C: the mean values with different letters are significantly different (ANOVA at the significance level $p = 0.05$).

Just before harvesting of the crop in 2016 and 2017, the soil from the 0–20 cm layer under strip-tilling, regardless of the place of sampling (row, inter-row), was characterized by a higher K content than from the 20–40 cm layer (Figure 6C,D). On the contrary, under plowing in 2016, the 20–40 cm layer was characterized by a higher concentration of K.

In 2016 and 2017, after sowing and at harvest, no differences were found in K content in the soil, on average for SL, in the compared tillage systems, between rows and inter-rows (Table 2).

The tillage method had a significant impact on P content in the soil after sowing green peas in both years of the study. In 2016, the soil under strip-tillage had a higher P content on average for SL and SP, while in 2017, the higher P content was under traditional cultivation (Figure 7A,B). Before the harvest of the crop, in both growing seasons, significantly larger amounts of P, on average for SL and SP, remained after strip-tilling than after traditional cultivation (Figure 7C,D).

The ST × SL interaction in 2016 indicates significant differences in soil P content after sowing between tillage systems only in the 0–20 cm soil layer (Figure 8A). In the deeper layer (20–40 cm), the content of P under the strip-till and plowing systems was similar. In turn, the P content analyzed independently in each of the two tillage systems was similar in both layers of the soil profile. Similarly, in 2017, the P content was similar in the analyzed soil layers under plowing, but under strip-tilling it was significantly higher in the 0–20 cm layer (Figure 8B).

Table 2. The content of available K in the soil in 2016 and 2017.

Year	Soil Tillage (ST)	Soil Layer (SL)	3 Weeks after Sowing		At Harvest	
			Sampling Place (SP)			
			Row	Inter-Row	Row	Inter-Row
2016	Plowing	0–20	242.4 ^{a} ± 2.27	235.8 ^{a} ± 27.4	165.0 ^{a} ± 6.46	157.5 ^{a} ± 7.70
		20–40	236.0 ^{a} ± 20.8	232.7 ^{a} ± 30.3	190.5 ^{a} ± 25.2	200.9 ^{a} ± 2.19
		Mean	239.2 ^{A} ± 13.7	234.2 ^{A} ± 25.9	177.7 ^{A} ± 21.6	179.2 ^{A} ± 24.3
	Strip-tilling	0–20	303.2 ^{a} ± 11.2	241.7 ^{a} ± 29.7	204.0 ^{a} ± 34.0	223.5 ^{a} ± 24.9
		20–40	203.6 ^{a} ± 18.3	214.6 ^{a} ± 8.69	159.2 ^{a} ± 8.65	154.8 ^{a} ± 6.46
		Mean	253.4 ^{A} ± 59.7	228.1 ^{A} ± 24.6	181.6 ^{A} ± 25.2	189.1 ^{A} ± 41.0
p-value			ST × SP = 0.314; ST × SL × SP = 0.095		ST × SP = 0.593; ST × SL × SP = 0.079	
2017	Plowing	0–20	170.0 ^{bc} ± 6.75	176.0 ^{b} ± 6.24	190.6 ^{a} ± 8.63	202.0 ^{a} ± 4.23
		20–40	169.1 ^{bc} ± 5.94	166.7 ^{bc} ± 8.02	199.2 ^{a} ± 7.26	203.7 ^{a} ± 3.39
		Mean	169.6 ^{A} ± 5.71	171.3 ^{A} ± 8.21	194.9 ^{A} ± 8.57	202.6 ^{A} ± 3.55
	Strip-tilling	0–20	211.0 ^{a} ± 15.15	188.1 ^{ab} ± 10.1	233.0 ^{a} ± 7.00	257.6 ^{a} ± 11.2
		20–40	139.4 ^{d} ± 7.58	148.9 ^{cd} ± 6.24	190.9 ^{a} ± 3.35	197.6 ^{a} ± 11.0
		Mean	175.2 ^{A} ± 40.7	168.5 ^{A} ± 22.7	212.0 ^{A} ± 23.6	227.6 ^{A} ± 34.3
p-value			ST × SP = 0.254; ST × SL × SP = 0.011		ST × SP = 0.236; ST × SL × SP = 0.393	

^{A}; $^{a–d}$—the mean values with different letters are significantly different (ANOVA at the significance level p = 0.05).

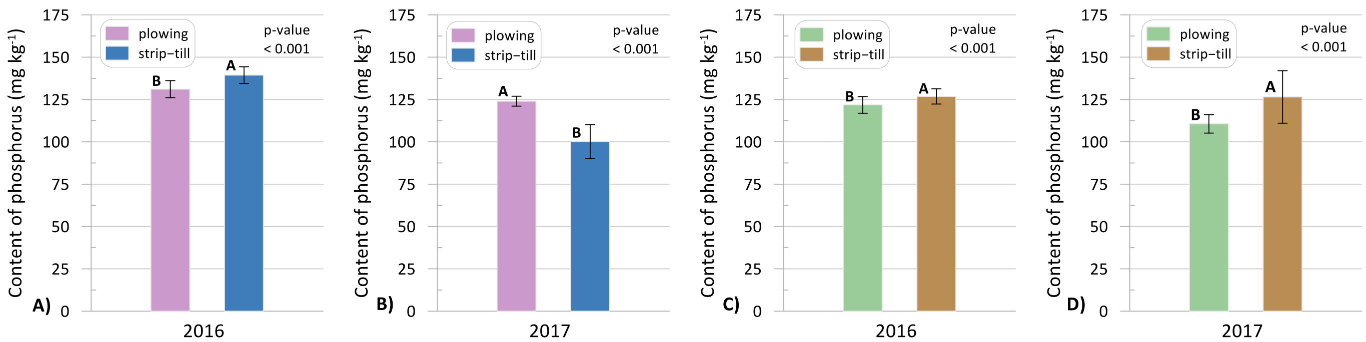

Figure 7. The content of available P: (**A**) 3 weeks after sowing in 2016; (**B**) 3 weeks after sowing in 2017; (**C**) at harvest in 2016; (**D**) at harvest in 2017. The values are the means for the sampling places (rows and inter-rows) and soil layers (0–20 and 20–40). A, B: the mean values with different letters are significantly different (ANOVA at the significance level p = 0.05).

The analysis of the ST × SL interaction indicates that, in both years of the study, the P content in the soil just before crop harvest, on average for SP, was significantly higher in the 0–20 cm soil layer under strip-tilling compared to the content in the same soil layer under plowing (Figure 8C,D). However, there was no such difference in the deeper soil layer (20–40 cm). Under the strip-till system in 2016 and 2017, the soil was characterized by a higher phosphorus content in the 0–20 cm soil layer. Under plowing in 2016, there was significantly more P in the deeper layer.

In both years of research and measurement dates, no differences were found in the P content in the soil, on average for SL, under plowing and strip-tilling, between rows and inter-rows (Table 3).

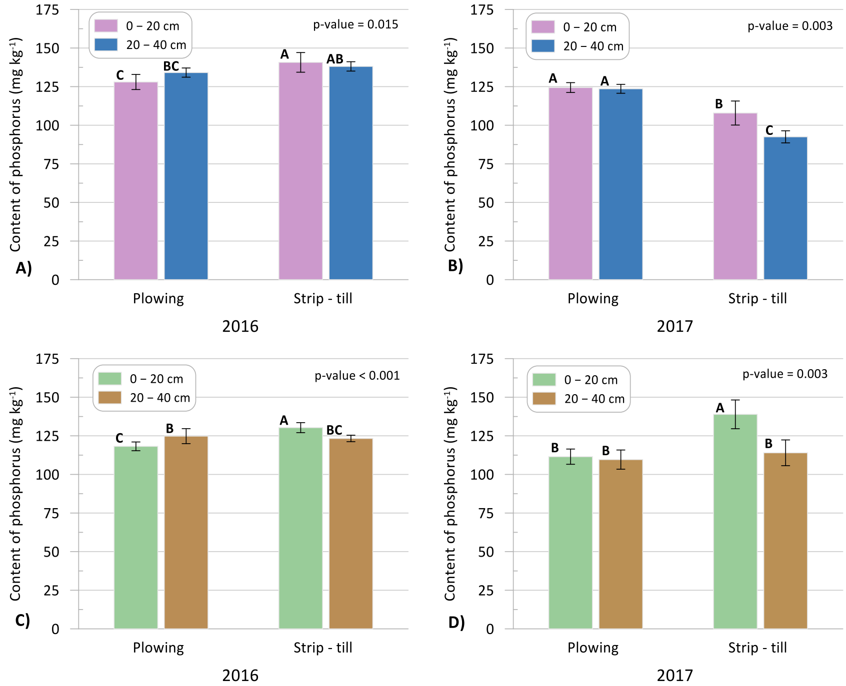

Figure 8. The content of available P in soil layers 0–20 cm and 20–40 cm: (**A**) 3 weeks after sowing in 2016; (**B**) 3 weeks after sowing in 2017; (**C**) at harvest in 2016; (**D**) at harvest in 2017. The values are the means for the sampling places (rows and inter-rows). A–C: the mean values with different letters are significantly different (ANOVA at the significance level $p = 0.05$).

Table 3. The content of available P in soil in 2016 and 2017.

Year	Soil Tillage (ST)	Soil Layer (SL)	3 Weeks after Sowing		At Harvest	
			Sampling Place (SP)			
			Row	Inter-Row	Row	Inter-Row
2016	Plowing	0–20	129.8 ^{a} ± 5.25	126.2 ^{a} ± 4.74	117.9 ^{a} ± 0.00	119.7 ^{a} ± 4.22
		20–40	133.1 ^{a} ± 3.75	135.1 ^{a} ± 2.25	122.2 ^{a} ± 4.35	127.3 ^{a} ± 4.54
		Mean	131.5 ^{A} ± 4.48	130.7 ^{A} ± 5.93	120.1 ^{A} ± 3.63	123.5 ^{A} ± 5.73
	Strip-tilling	0–20	144.8 ^{a} ± 4.52	136.5 ^{a} ± 5.46	127.4 ^{a} ± 1.44	133.1 ^{a} ± 0.00
		20–40	140.6 ^{a} ± 0.75	135.6 ^{a} ± 1.91	122.4 ^{a} ± 1.91	124.1 ^{a} ± 2.26
		Mean	142.7 ^{A} ± 3.70	135.1 ^{A} ± 3.70	124.9 ^{A} ± 3.14	128.6 ^{A} ± 5.13
	p-value		ST × SP = 0.089; ST × SL × SP = 0.717		ST × SP = 0.912; ST × SL × SP = 0.147	
2017	Plowing	0–20	125.1 ^{a} ± 2.54	123.6 ^{a} ± 4.17	110.6 ^{a} ± 5.02	112.4 ^{a} ± 4.17
		20–40	125.1 ^{a} ± 2.54	122.0 ^{a} ± 2.65	108.8 ^{a} ± 3.54	110.5 ^{a} ± 9.06
		Mean	125.1 ^{A} ± 2.27	122.8 ^{A} ± 3.25	109.7 ^{A} ± 4.01	111.5 ^{A} ± 6.88
	Strip-tilling	0–20	110.2 ^{a} ± 11.1	105.5 ^{a} ± 3.46	136.8 ^{a} ± 13.3	141.1 ^{a} ± 5.02
		20–40	91.2 ^{a} ± 5.63	93.8 ^{a} ± 1.17	111.2 ^{a} ± 10.2	116.8 ^{a} ± 6.85
		Mean	110.7 ^{A} ± 13.1	99.7 ^{A} ± 6.79	124.0 ^{A} ± 17.6	129.0 ^{A} ± 14.4
	p-value		ST × SP = 0.763; ST × SL × SP = 0.292		ST × SP = 0.626; ST × SL × SP = 0.912	

^{A}; ^{a}—the mean values with different letters are significantly different (ANOVA at the significance level $p = 0.05$).

In 2016, the analysis of Mg content after sowing and at harvest of green peas did not show significant differences, neither for main effects nor for interactions (Figures 9A,C and 10A,C). In 2017, after sowing, strip-till technology increased the average Mg content in the soil for SL and SP compared to traditional cultivation (Figure 9B). In the same year, before harvest, there were differences in Mg between strip-tilling and plowing in the layers, with a higher content in the surface layer under strip-tilling (Figure 10D).

In 2017, the ST × SP interaction indicates that the increase in Mg content in the soil after sowing under strip-till technology compared to plowing occurred in the row (Table 4).

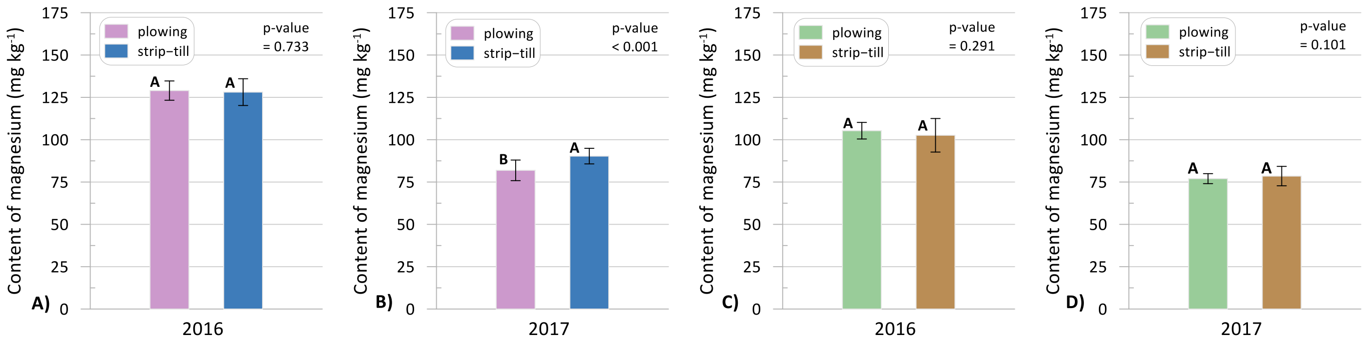

Figure 9. The content of available Mg: (**A**) 3 weeks after sowing in 2016; (**B**) 3 weeks after sowing in 2017; (**C**) at harvest in 2016; (**D**) at harvest in 2017. The values are the means for the sampling places (rows and inter-rows) and soil layers (0–20 and 20–40). A, B—the mean values with different letters are significantly different (ANOVA at the significance level $p = 0.05$).

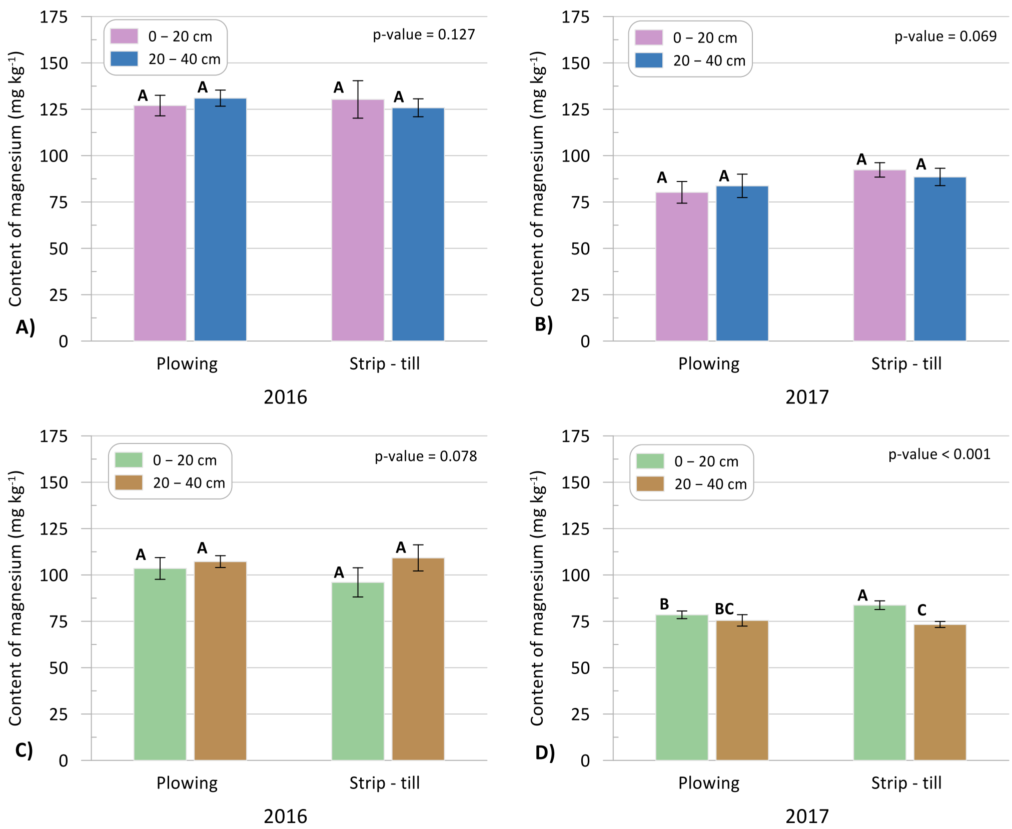

Figure 10. The content of available Mg in soil layers 0–20 cm and 20–40 cm: (**A**) 3 weeks after sowing in 2016; (**B**) 3 weeks after sowing in 2017; (**C**) at harvest in 2016; (**D**) at harvest in 2017. The values are the means for the sampling places (rows and inter-rows). A–C: the mean values with different letters are significantly different (ANOVA at the significance level $p = 0.05$).

Table 4. The content of available Mg in the soil in 2016 and 2017.

Year	Soil Tillage (ST)	Soil Layer (SL)	3 Weeks after Sowing		At Harvest	
			Sampling Place (SP)			
			Row	Inter-Row	Row	Inter-Row
2016	Plowing	0–20	126.0 [a] ± 8.19	128.0 [a] ± 6.08	105.0 [a] ± 4.00	102.0 [a] ± 7.94
		20–40	132.0 [a] ± 3.61	130.0 [a] ± 5.57	106.7 [a] ± 4.73	107.7 [a] ± 1.53
		Mean	129.0 [A] ± 6.54	129.0 [A] ± 5.33	105. 8 [A] ± 4.02	104.8 [A] ± 5.98
	Strip-tilling	0–20	125.3 [a] ± 0.58	135.3 [a] ± 13.4	92.0 [a] ± 8.72	100.0 [a] ± 5.57
		20–40	121.7 [a] ± 1.53	130.0 [a] ± 2.00	112.3 [a] ± 9.07	106.0 [a] ± 3.46
		Mean	123.5 [A] ± 2.26	132.7 [A] ± 9.07	102.2 [A] ± 13.7	103.0 [A] ± 5.29
	p-value		ST × SP = 0.102; ST × SL × SP = 0.828		ST × SP = 0.721; ST × SL × SP = 0.088	
2017	Plowing	0–20	76.3 [a] ± 1.53	84.0 [a] ± 6.24	78.0 [a] ± 1.73	79.0 [a] ± 2.65
		20–40	80.3 [a] ± 1.53	87.0 [a] ± 8.00	73.3 [a] ± 1.15	77.7 [a] ± 2.89
		Mean	78.3 [B] ± 2.58	85.5 [AB] ± 6.63	75.7 [A] ± 2.88	78.3 [A] ± 2.58
	Strip-tilling	0–20	92.0 [a] ± 5.29	92.7 [a] ± 3.06	82.7 [a] ± 0.58	84.7 [a] ± 3.21
		20–40	91.0 [a] ± 5.20	85.7 [a] ± 2.52	72.7 [a] ± 1.53	74.0 [a] ± 1.73
		Mean	91.5 [A] ± 4.72	89.2 [A] ± 4.58	77.7 [A] ± 5.57	79.3 [A] ± 6.28
	p-value		ST × SP = 0.025; ST × SL × SP = 0.526		ST × SP = 0.570; ST × SL × SP = 0.263	

[A,B]; [a]—the mean values with different letters are significantly different (ANOVA at the significance level $p = 0.05$).

3.2. Length and Dry Matter Weight of Green Pea Shoots and Roots

In 2016, the length of green pea shoots measured 7 weeks after sowing was significantly higher under strip-till technology. The stimulating effect of strip-tilling on the length of shoots was also found 11 weeks after sowing (during the period of pod development). The response of the green peas' root length in the analyzed year of the study was similar. After 7 and 11 weeks after sowing, respectively, it was significantly higher in plants grown under strip-tilling compared to plowing. In 2017, there was no significant impact of the cultivation system on the length of shoots or roots at any of the analyzed measurement dates (Table 5).

Table 5. Length and dry matter weight of green pea shoots and roots.

Year	Soil Tillage (ST)	7 Weeks after Sowing		11 Weeks after Sowing	
		Length (cm)			
		Shoots	Roots	Shoots	Roots
2016	Plowing	15.4 [b] ± 0.82	10.5 [b] ± 1.03	54.9 [b] ± 1.59	12.3 [b] ± 1.20
	Strip-tilling	18.0 [a] ± 1.38	16.6 [a] ± 1.86	64.8 [a] ± 1.35	19.3 [a] ± 2.17
p-value		ST = 0.019	ST < 0.001	ST = 0.001	ST = 0.001
2017	Plowing	20.9 [a] ± 1.04	11.3 [a] ± 1.00	56.2 [a] ± 2.40	12.8 [a] ± 1.78
	Strip-tilling	19.8 [a] ± 1.75	11.9 [a] ± 0.44	56.7 [a] ± 2.33	15.6 [a] ± 1.59
p-value		ST = 0.320	ST = 0.750	ST = 0.384	ST = 0.059
		Dry matter weight (g m^2)			
2016	Plowing	20.1 [b] ± 1.76	2.00 [b] ± 0.31	307.6 [a] ± 23.7	8.83 [a] ± 1.39
	Strip-tilling	27.4 [a] ± 3.02	5.19 [a] ± 1.13	347.1 [a] ± 29.3	8.39 [a] ± 1.22
p-value		ST = 0.006	ST = 0.002	ST = 0.081	ST = 0.226
2017	Plowing	52.5 [a] ± 1.68	8.39 [a] ± 1.02	277.5 [a] ± 20.6	9.93 [a] ± 0.67
	Strip-tilling	56.2 [a] ± 3.03	8.28 [a] ± 0.56	298.6 [a] ± 11.8	11.44 [a] ± 1.20
p-value		ST = 0.073	ST = 0.857	ST = 0.125	ST = 0.070

[a,b]—the mean values with different letters are significantly different (ANOVA at the significance level $p = 0.05$).

In 2016, the dry matter of green pea shoots measured 7 weeks after sowing was significantly higher under strip-till technology compared to plowing. The dry matter of roots in the same period was also higher under strip-tilling. In the analyzed year of the study, there was no significant effect of the cultivation system on the dry weight of shoots or roots 11 weeks after sowing. In 2017, the cultivation system had no significant effect on the dry weight of shoots or roots (Table 5).

3.3. Content of Macroelements in the Biomass and Their Uptake by Green Peas

In 2016, the N content in the total biomass of green peas 7 weeks after sowing was significantly higher under the plowing system compared to strip-till technology. In turn, N uptake by plants at the same date was significantly higher under the strip-till system. Eleven weeks after sowing (during the pod development period), N content in green peas was higher under strip-tilling. This technology also facilitated the uptake of larger amounts of N at this stage of plant development. In 2017, the N content in plants and its uptake after 7 and 11 weeks after sowing were not influenced by the tillage system (Table 6).

Table 6. The content and uptake of N and K by green pea plants in 2016 and 2017.

Year	Soil Tillage (ST)	7 Weeks after Sowing		11 Weeks after Sowing	
		Content %	Uptake kg ha^{-1}	Content %	Uptake kg ha^{-1}
			N		
2016	Plowing Strip-tilling	$6.16^{a} \pm 0.17$ $5.82^{b} \pm 0.20$	$13.6^{b} \pm 1.41$ $19.0^{a} \pm 2.35$	$3.56^{b} \pm 0.15$ $3.99^{a} \pm 0.18$	$112.8^{b} \pm 9.54$ $142.1^{a} \pm 15.1$
p-value		ST = 0.043	ST = 0.008	ST = 0.011	ST = 0.017
2017	Plowing Strip-tilling	$4.80^{a} \pm 0.03$ $4.73^{a} \pm 0.18$	$29.2^{a} \pm 0.97$ $30.5^{a} \pm 1.66$	$3.16^{a} \pm 0.16$ $3.18^{a} \pm 0.08$	$91.0^{a} \pm 9.56$ $98.7^{a} \pm 5.54$
p-value		ST = 0.454	ST = 0.227	ST = 0.829	ST = 0.212
			K		
2016	Plowing Strip-tilling	$4.58^{a} \pm 0.33$ $4.40^{a} \pm 0.16$	$10.2^{b} \pm 1.49$ $14.4^{a} \pm 1.68$	$3.32^{a} \pm 0.25$ $3.38^{a} \pm 0.08$	$104.9^{b} \pm 6.47$ $119.9^{a} \pm 7.66$
p-value		ST = 0.354	ST = 0.010	ST = 0.685	ST = 0.024
2017	Plowing Strip-tilling	$4.88^{a} \pm 0.31$ $5.01^{a} \pm 0.20$	$29.7^{a} \pm 2.10$ $32.4^{a} \pm 2.79$	$3.50^{a} \pm 0.37$ $3.38^{a} \pm 0.56$	$101.1^{a} \pm 18.2$ $104.7^{a} \pm 15.5$
p-value		ST = 0.494	ST = 0.174	ST = 0.744	ST = 0.774

[a,b]—the mean values with different letters are significantly different (ANOVA at the significance level $p = 0.05$).

In 2016, the content of K in the green peas' biomass, assessed 7 and 11 weeks after sowing, respectively, was similar in both tillage methods. However, K uptake in the first year of the study was the highest when green peas were grown under strip-till technology, both 7 and 11 weeks after sowing. In 2017, it was found that the K content determined in plants, as well as the uptake of this element, similarly to nitrogen, did not depend on the type of tillage on either of the two measurement dates ($p > 0.05$) (Table 6).

The P content in the total biomass of pea plants 7 weeks after sowing in 2016 was similar in both tillage systems. In turn, the intake of this element 7 weeks after sowing was higher (by 43.0%) under strip-till technology as compared to plowing. At a later date of measurement (11 weeks after sowing), both the content and uptake of this nutrient by the plant were significantly higher under the strip-till system than under plowing. In 2017, on both assessment dates, the content of P in plant biomass and its uptake were not determined by the tillage system (Table 7).

Table 7. The content and uptake of P and Mg by green pea plants in 2016 and 2017.

Year	Soil Tillage (ST)	7 Weeks after Sowing		11 Weeks after Sowing	
		Content %	Uptake kg ha^{-1}	Content %	Uptake kg ha^{-1}
			P		
2016	Plowing Strip-tilling	0.365 ^{a} ± 0.014 0.358 ^{a} ± 0.015	0.825 ^{b} ± 0.096 1.18 ^{a} ± 0.171	0.253 ^{b} ± 0.013 0.290 ^{a} ± 0.008	8.03 ^{b} ± 0.846 10.3 ^{a} ± 0.931
p-value		ST = 0.507	ST = 0.012	ST = 0.002	ST = 0.011
2017	Plowing Strip-tilling	0.330 ^{a} ± 0.022 0.315 ^{a} ± 0.030	2.00 ^{a} ± 0.183 2.03 ^{a} ± 0.320	0.228 ^{a} ± 0.017 0.240 ^{a} ± 0.014	6.53 ^{a} ± 0.602 7.45 ^{a} ± 0.661
p-value		ST = 0.448	ST = 0.868	ST = 0.303	ST = 0.084
			Mg		
2016	Plowing Strip-tilling	0.363 ^{a} ± 0.010 0.363 ^{a} ± 0.010	0.825 ^{b} ± 0.096 1.18 ^{a} ± 0.150	0.356 ^{a} ± 0.005 0.348 ^{a} ± 0.010	11.3 ^{a} ± 0.849 12.3 ^{a} ± 0.735
p-value		ST = 1.00	ST = 0.008	ST = 0.114	ST = 0.125
2017	Plowing Strip-tilling	0.275 ^{a} ± 0.006 0.283 ^{a} ± 0.026	1.68 ^{a} ± 0.096 1.83 ^{a} ± 0.126	0.290 ^{b} ± 0.024 0.340 ^{a} ± 0.000	8.33 ^{b} ± 0.222 10.6 ^{a} ± 0.387
p-value		ST = 0.598	ST = 0.126	ST = 0.006	ST = <0.001

[a,b]—the mean values with different letters are significantly different (ANOVA at the significance level $p = 0.05$).

The biomass of green peas in the first year of the study contained similar amounts of Mg in both cultivation systems. Only in the first analysis period (7 weeks after sowing), in green peas grown under strip-till technology, a significantly higher intake of this element was found as compared to under plowing (Table 7).

Unlike N, P, and K, the analysis results for Mg in 2017 indicate that the content in the plant and the intake of this macronutrient were, to a greater extent, influenced by the tillage system. For measurements taken 11 weeks after sowing, a significant, stimulating effect of strip-till technology on the Mg content in biomass and its uptake by green peas was found (Tables 6 and 7).

3.4. Seed Yield and Yield Components

In both 2016 and 2017, the type of tillage did not affect the plant density of green peas. The analysis of the number of pods per plant showed a significant impact of tillage on this yield component in 2016. In this year of the study, strip-tillage resulted in an increased number of pods per pea plant. In turn, in 2017, there was no impact of the tillage system on the number of pods produced by plants (Figure 11).

The tillage had no influence on the number of seeds per pod in any of the growing seasons. Similarly, there was no effect of plowing or strip-tilling on the 1000-seed weight. The seed yield, as with the number of pods per plant, was influenced by the tillage only in the first year of the study. It was noticed that, in 2016, green peas gave a higher yield when grown under the strip-till system (Figure 11).

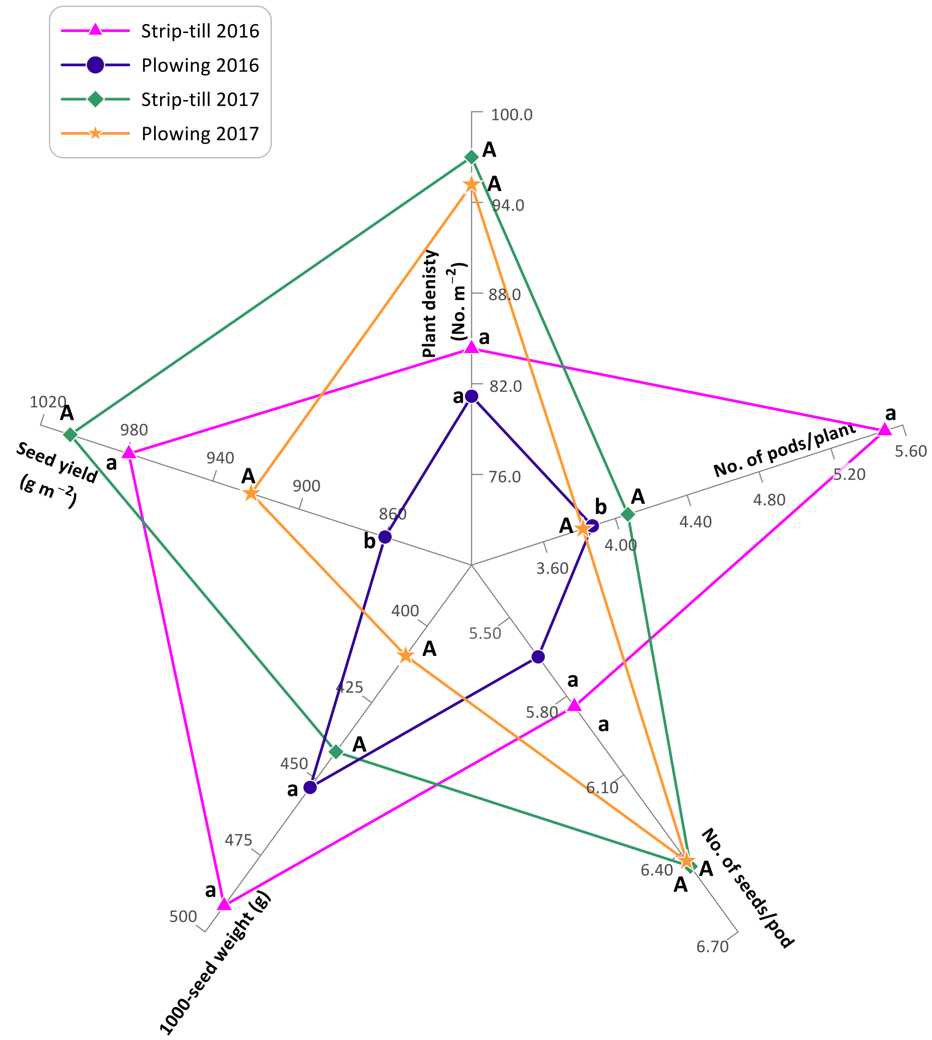

Figure 11. Yield and yield components of the green peas, depending on soil tillage methods in 2016 and 2017. A, a, b—the mean values with the same letters are not significantly different (ANOVA at the significance level $p = 0.05$).

4. Discussion

The tillage and fertilization systems used in the study (strip-tilling and plowing) had a different effect on the content of individual macroelements in the soil. Moreover, the content of NPK and Mg in the soil depended on the place of sampling (row vs. inter-row) and the layer of the soil profile (0–20 or 20–40 cm). The date of measurement and the weather during the growing season were also of crucial importance.

N is one of the most important nutrients necessary for the proper growth and development of plants [33]. In our study, both in 2016 and 2017, three weeks after green pea sowing, the soil under strip-tillage was characterized by a higher content of mineral nitrogen available to plants, on average for SL and SP (Figure 3A,B). Moreover, in this technology, a higher content of N was recorded in rows than in inter-rows (Table 1). In both years of the study, three weeks after sowing and before harvest, there was generally more mineral N in the 20 cm soil layer under strip-tillage compared to plowing (Figure 4). The above effects result from the technique of applying fertilizers, which are placed deep in the soil and only in cultivated strips [34]. In turn, under the plowing system, N fertilizers are broadcasted on the soil surface and then mixed with the top layer of soil, loosened to the depth of the previously made plowing. This system of soil cultivation and fertilization causes nitrogen losses through the emission of N_2O and NH_3 into the atmosphere, as well as surface runoff or leaching of nutrients deep into the soil profile [35], which could have contributed to the reduced content of N in the soil under conventional cultivation in our study. The research conducted in this area by Li et al. [36] indicates higher amounts of N in the soil when it was introduced deep into the soil profile, rather than after surface broadcast, which is similar to our results. The increase in the amount of N in the soil under strip-tillage may also result from the accumulation of a larger amount of plant residues in this soil cultivation system, and thus the content of organic matter in the soil, which is an important source of nutrients [37]. Overall, in our study, there was a lower soil N content three weeks after sowing in 2017 than in 2016 (Figure 3A,B). This may be due to higher rainfall in the second year of the study (Figure 1), which may contribute to some N leaching into the soil profile [38]. In 2017, increased rainfall was recorded from the beginning of the growing season, while in 2016, heavy rainfall occurred only in July, after the pea harvest. Despite higher rainfall, in the second year, more N was still determined in the soil under reduced tillage than under traditional tillage. This allows us to claim that this system contributes to better availability of N for plants, originating from mineral fertilization in various weather conditions during the growing seasons.

In 2016, the hydrothermal conditions (Figure 1) were less favorable for peas due to higher temperatures and lower rainfall occurring between April (sowing date) and the beginning of July (harvest time). However, despite these weather conditions, strip-tillage resulted in higher shoot dry matter and nitrogen uptake 7 weeks after sowing, as well as higher nitrogen content and uptake by peas during the period of seed development (11 weeks after sowing) (Tables 5 and 6). This may be due to the placement of this element within the root system, which increased its availability [39]. Moreover, in our study in 2016, strip-tilling promoted the elongation of roots and increased their mass (Table 5). As Grüner et al. [40] pointed out, the greater the root biomass, the more intense N fixation by legumes can be, which can explain the much higher N uptake by green peas under that tillage system in our study. The positive impact of strip-tilling on the increase in plant biomass (Table 5) and nitrogen accumulation (Table 6) in 2016 could also result from better soil moisture in the sowing strips, as indicated by research by Jaskulski [41]. According to other researchers [42,43], water availability is one of the most important factors affecting the uptake of macroelements by plants during growth. The improvement of the physical properties of the soil as a result of the use of strip-tillage, confirmed by the studies of Fernández et al. [44], Moraru et al. [45], and Stankowski et al. [46], may also be of some importance.

K in legumes is necessary for the proper synthesis of protein-building amino acids and it is involved in the construction of tissues that ensure the mechanical stability of plants and supports seed formation [47]. In our study, 3 weeks after sowing as well as before harvesting, the K content in the 0–20 cm soil layer was higher under strip-tillage compared to plowing. Moreover, under strip-tillage, in both seasons, there was significantly more K in the 0–20 layer than in the 20–40 cm layer (Figure 6). As other researchers report [48], this is mainly due to the technique and depth of fertilizer placement by machines for this type of cultivation. Moreover, more organic matter is accumulated in simplified cultivation, which may increase the effect of concentrating this macroelement in the arable soil layer [49].

In both years of the study under plowing, there was less K in the 0–20 cm soil layer before harvesting green peas than in the 20–40 cm layer, even though its initial content was similar in both soil layers (Figure 6C,D). This could be due to the shallower root system of peas in this treatment (Table 5) and the absorption of this element by plants only from the arable layer.

K uptake in both measurement dates in 2016 was higher under strip-tilling than plowing (Table 6). Our results are consistent with those obtained in the analysis of the influence of the depth of fertilizer placement on the uptake of macroelements by soybean [50]. The author noticed that K fertilizer applied on the subsurface (as under strip-tilling) was taken up by plants in larger amounts than fertilizer applied on the surface (as under plowing). Moreover, in our studies, plants grown under strip-tillage developed longer roots and a larger root mass (Table 5), facilitating the uptake of nutrients and water, which stimulated the growth of pea biomass and the accumulation of macroelements.

P is the second most important macroelement for plants after N [51] and its sufficient amount, availability, and undisturbed uptake is essential for proper plant growth, especially for roots [52]. In legumes, P is particularly important because it is necessary for the proper activity of the nitrogenase enzyme, which is responsible for the formation of root nodules and N2 fixation [53]. In our research, the method of soil cultivation and fertilization influenced the spatial distribution of P in the soil and its uptake by plants.

The analysis of P content in the soil three weeks after sowing indicates that, under plowing, both in 2016 and 2017, the distribution of P in the 0–20 and 20–40 cm soil layers was similar (Figure 8A,B). In turn, under strip-tillage in 2017, there was more P in the 0–20 cm soil layer than in the 20–40 cm layer. Similar results were obtained in many studies, where P content in the soil, after deep fertilization using strip-till equipment, tends to be higher in the 10–20 cm soil layer [8,48]. In general, Nze Memiaghe et al. [54] claim that the distribution of phosphorus in the soil profile is more even under conventional than conservation tillage. Stankowski et al. [46] state that the distribution of P in the soil profile is more even in under conventional cultivation than in the case of conservation cultivation, which is caused by frequent mixing and turning of the soil in the plow system. In conservation tillage, phosphorus accumulates in the shallower soil layer because it is less mobile.

The amount of P in the soil before harvesting green peas in 2016 was shaped by the same factors that affected its amount 3 weeks after sowing (Figures 7C,D and 8C,D, Table 3). P content in the arable layer was higher under strip-tilling than plowing (Figure 8C). As in the case of K and N, this was the result of a higher content of P in this soil layer after pea sowing. This higher content of available P in soil stimulated plant growth and resulted in increased uptake of this nutrient by green peas under strip-till technology (Table 7). The increased root mass of peas could have contributed to the higher P uptake in this tillage system (Table 5).

In 2017, the P content in the soil before harvesting green peas was different than three weeks after sowing. After sowing, more P was found under plowing than strip-tilling, while, before harvesting, the most P was in the 0–20 cm layer under strip-tilling (Figures 7B and 8D). As emphasized by Meyer et al. [55], P availability in soil depends on many interdependent factors, including soil properties (e.g., buffering capacity, ion availability, pH, bulk density, content of organic matter), type of fertilizer, and water availability in the profile. In our study, higher rainfall in 2017 (Figure 1) may have contributed to a different phosphorus management in the soil profile than in 2016. However, it is difficult to clearly determine the impact of the cultivation and fertilization system on its content and lability in the soil. This indicates the need for further research on the effect of the application technique of this macronutrient in order to increase its availability for plants.

In addition to basic macroelements (NPK), Mg is also necessary for plant growth and development. It is a basic component of chlorophyll and is involved in the transport of assimilates from leaves to sink organs, which makes it responsible for the proper course of the photosynthesis process and assimilate management. Moreover, Mg affects the utilization of N [56] and plant resistance for biotic and abiotic stresses [57].

In our study, Mg turned out to be an element that responded relatively little to the factors used in the experiment. In the first year of the study, there was no reaction of magnesium content to the tillage system and the layer and place of sampling. There was also no interaction of factors influencing the content of this macroelement in the soil three weeks after sowing green peas, as well as before harvest (Table 4, Figures 9A,C and 10A,C). Similarly, Biskupski et al. [58] showed no effect of the tillage system on the amount of Mg in the 0–40 cm soil layer.

However, in the second year of the study, under reduced tillage (strip-till), higher amounts of Mg were found, especially in the sowing zone of the cultivated plant, compared to conventional cultivation (Table 4, Figures 9B,D and 10B,D), which is consistent with the results of Stankowski et al. [46]. This had a beneficial effect on the uptake of this element by plants (Table 7). Mg is an element characterized by high mobility in the soil, and its content is regulated by many interdependent factors, such as water availability and the content of other ions in the soil solution [59,60]. In our research in 2017, the reduced amount of this element under plowing could result from its increased leaching from the inverted and highly loosened soil in this traditional tillage system due to high rainfall. The process of leaching nutrients from the soil is particularly intense when the organic matter content is low, which is often shown as a disadvantage of plowing tillage [61].

In our study in 2016, a beneficial effect of strip-till technology on the length of shoots and roots, the dry matter of shoots, number of pods per plant, and green pea yield has been demonstrated (Table 5, Figure 11). In turn, in 2017, there were no statistically proven differences in the length and weight of shoots and roots (Table 5), N and K uptake (Table 6), seed yield, or yield components (plant density, pods per plant, seeds per pod, 1000-seed weight) between reduced and conventional tillage (Figure 11). The above differences result mainly from different weather conditions during the study years (2016 was warm and dry; 2017 had higher air temperatures and more precipitation) (Figure 1). Similarly, other studies have shown that legume productivity depends more on weather conditions than on the tillage system [61,62]. In dry conditions, the productivity of legumes is generally higher in reduced tillage [63]. The remaining uncultivated strips, with crop residues and retained soil structure, allow better retention of the moisture needed for plants to emerge and grow. However, some studies in areas with high rainfall and low temperatures suggest that conventional tillage may be a more effective system due to better soil loosening, soil uncovering, and the potential for excessive water run-off, allowing the soil to warm up [64]. As Faligowska et al. [19] pointed out, it is difficult to determine the effect of a particular tillage system (conventional or reduced) on legumes because of their dependence on factors such as temperature, rainfall, and their distribution throughout the growing season. Further research should be conducted to better understand the impact of the interaction of tillage methods and climatic conditions on pea productivity.

In our study, green pea yield in 2017 was significantly higher under strip-tilling than under plowing. The beneficial effect of the reduced tillage on the yield of legumes was confirmed by other researchers [65–67]. This is attributed to higher content of organic matter, better nutrient availability [68], and increased microbial biomass and their activity in the soil [69]. Nowadays, the activity of soil bacteria is increasingly recognized as playing an important role in the availability of plant nutrients and the shaping of the yield and yield structure [70]. Environmental and climatic conditions, as well as seasonal weather patterns (temperature, precipitation), have a major impact on their enzyme activity [71]. Moreover, the enzymatic activity of microorganisms is significantly influenced by the type of soil cultivation and is generally greater under reduced tillage [72]. Microorganisms are involved in the decomposition of organic matter and the conversion of elements into bio-available forms to plants, which in turn influences plant growth and development [73]. The above relationships and processes could be one of the reasons for the stronger response of plants to tillage systems in 2016. Probably, the conditions of lower rainfall in the first year of the study, and the higher soil moisture under strip-cultivation compared to plowing, promoted the increase in the activity of soil microorganisms, creating better conditions for plant growth during the growing season, as indicated by the pea growth and yield parameters. However, more research should be conducted to confirm our hypothesis, especially because the pea is a plant whose proper growth is closely related to the activity of symbiotic nitrogen-fixing bacteria.

The results presented in our study confirm the positive effect of strip-tillage compared to plow tillage, as indicated by other researchers [7,74,75]. Its significant advantage is targeted fertilization concentrated in the sowing zone, which increases the content of soil nutrients in the immediate vicinity of plant roots. This situation favors a better supply of plants with nutrients [44], stimulating the dynamics of initial plant growth while preventing losses of macro- and microelements [37,76]. As our research showed, increased availability of minerals under strip-tillage resulted in an increase in pea plant biomass and increased seed yield. The literature contains many reports on increasing plant yields as a result of replacing plow tillage with reduced tillage [74,77]. However, the effects of using strip-till technology depend largely on weather conditions, which was also confirmed by our research. A particularly beneficial effect of simplifications is observed in dry years [78–80]. The results of our study indicate a significant protective effect of strip-tillage and sowing on the soil, confirming, as a rule, a higher content of nitrogen and potassium in the shallower soil layer (0–20 cm) (Tables 1 and 2) compared to plow tillage. Dumanski et al. [76] and Gruber et al. [81] suggested that strip-tillage can have both a positive effect on production due to concentrated strip fertilization and a positive effect on the environment by reducing the risk of eutrophication.

5. Conclusions

Tillage and fertilization technology, strip-tilling (reduced) and plowing (conventional), have influenced the spatial distribution of nutrients in the soil, their content and uptake by plants during the growing season, shoot and root growth, and yield of green peas.

The strip-tillage resulted in an increase in N content in the sowing strip compared to inter-rows. Moreover, this technology has led to a higher content of N and K in the topsoil (0–20 cm), which stimulated an increase in the uptake of these nutrients by plants.

Strip-tilled plants developed greater dry weight and longer shoots and roots, a larger number of pods per plant, and a higher seed yield (by 13.8%) than plants grown under a plowing system. In turn, reduced tillage was found to be insignificant when the weather during the growing season was more favorable for crop development.

The above indicates that strip-till technology has a positive impact on the cultivation of green peas, especially in adverse weather conditions. Due to the increasing frequency of periods with water shortages and higher temperatures, this technology is recommended to achieve better yields while promoting sustainable agricultural production.

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