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ORIGINAL PAPER

Effects of soil compaction and reduced tillage on soil properties and maize yield*

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Abstract

Preceding crops, soil compaction and tillage are key management factors influencing soil chemical properties and crop performance. However, their combined effects, particularly under on-farm conditions, remain insufficiently recognized. The aim of this study was to evaluate the effects of preceding crops (multi-species grassland and winter triticale), soil compaction and tillage systems on selected soil chemical properties and maize (*Zea mays* L.) silage yield. The field experiment was conducted under production conditions using a factorial strip-split-plot design. Soil samples were analysed for pH, soil organic carbon (SOC), total nitrogen, the C:N ratio and the availability of phosphorus, potassium and magnesium. Maize silage yield was determined at harvest. The preceding crop significantly affected soil pH and the availability of macronutrients, whereas its influence on SOC and total nitrogen was limited when considered as a main factor. Soil compaction resulted in only minor changes in soil chemical properties, reflecting a relatively low level of compaction. Tillage systems had a significant impact on soil chemical properties; however, their effects were often modulated by interactions with other factors, and no significant main effect on maize yield was observed. Maize silage yield was 12.9% higher after grassland than after winter triticale. Our findings demonstrate that preceding crops exert a stronger influence on soil chemical properties and maize yield than a tillage system or soil compaction. The effects of tillage and compaction were mainly expressed through interactions, highlighting the importance of integrated management approaches in assessments of soil fertility.

Keywords: preceding crops, soil packing, soil tillage, macronutrients

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INTRODUCTION

Crop rotation and soil tillage are key determinants of soil chemical properties and nutrient cycling, playing a fundamental role in maintaining soil fertility and sustainable crop production (Lal 2004, Johnston et al. 2009). Preceding crops influence soil pH, nutrient availability and soil organic matter through differences in residue quality, nutrient uptake and rhizosphere processes (Drinkwater et al. 1998, Kuzyakov, Domanski 2000). Diverse crop rotations enhance nutrient retention and internal cycling, whereas simplified rotations may reduce soil buffering capacity and increase nutrient losses.

Nevertheless, modern agricultural systems increasingly rely on simplified crop rotations, often dominated by cereals, under the assumption that mineral fertilization can compensate for reduced biological diversity. Numerous studies have shown that such simplifications may negatively affect soil chemical status, leading to declines in soil organic carbon (SOC), nutrient imbalance and reduced long-term soil fertility (Karlen et al. 1994, Tilman et al. 2002).

Maize (*Zea mays* L.) is a crop with high nutrient requirements and therefore represents a suitable model for assessing changes in soil chemical properties induced by management practices (Hirel et al. 2007, Ciampitti, Vyn 2014). Favourable preceding crops, such as legumes or grasslands, are often reported to improve soil nutrient status, whereas cereals are considered less beneficial. However, published results remain inconsistent, particularly with respect to soil organic carbon (SOC) and total nitrogen, which may respond slowly to changes in crop rotation (West, Post 2002, Poeplau, Don 2015). These discrepancies are largely attributed to site-specific factors, including soil type, climate and management intensity (Karlen et al. 2013).

Soil tillage and compaction further modify soil chemical properties by influencing organic matter turnover, nutrient stratification and ion mobility (Six et al. 2000, Soane et al. 2012). Conventional ploughing tends to accelerate organic matter mineralization and homogenize nutrient distribution within the plough layer, whereas reduced tillage systems often promote the accumulation of SOC and nutrients in surface soil horizons (Franzluebbers 2002, Blanco-Canqui, Lal 2008). These processes may affect nutrient availability for crops and alter soil chemical gradients. At the same time, increasing machinery loads contribute to soil compaction, potentially altering soil pH and the availability of macroelements. Soil compaction may indirectly influence soil chemical properties by restricting root growth, modifying soil aeration and altering nutrient uptake patterns (Hamza, Anderson 2005, Batey 2009). Although individual effects of tillage and compaction have been widely studied, their combined impact and interactions with preceding crops remain less clearly understood, particularly under on-farm conditions.

Grasslands as preceding crops are still underrepresented in studies focusing on maize cultivation and soil chemical properties, despite their potential to improve nutrient cycling and soil quality.

Moreover, many studies address tillage, compaction or crop rotation separately, whereas their combined effects are likely to be more relevant under practical farming conditions.

Therefore, the objective of this study was to evaluate the effects of preceding crops (multi-species grassland and winter triticale), soil compaction and tillage systems on selected soil chemical properties and maize silage yield under production conditions.

Based on the identified research gaps, we formulated the following hypotheses: (i) preceding crops, particularly multi-species grassland, exert a more profound influence on soil chemical properties and maize yield than tillage systems or moderate soil compaction; (ii) the response of soil nutrient availability and organic carbon to reduced tillage is highly dependent on the preceding crop and the degree of soil packing; and (iii) the beneficial legacy effects of grassland will result in higher maize silage yields compared to winter triticale, regardless of the tillage intensity or mild soil compaction.

MATERIALS AND METHODS

Field experiment

The on-farm experiment was conducted between 2017 and 2020 on a Bałowo farm (53°53′49″ N, 21°10′38″ E, 160 m a.s.l.), located in north-eastern Poland. Each year, maize was cultivated in two production fields, each with an area of 10 ha, and the preceding crops for maize were grassland and winter triticale. A three-factorial field experiment with a strip-split-plot design was set up. The experimental factors were as follows: factor A (whole plots) – preceding crops (2-year multi-species grassland; winter triticale); factor B (strip plots) – degree of pre-sowing soil packing (control plot without packing; plot with soil packing after harvesting the preceding crop – a pass of a tractor + trailer combination with a weight of approximately 9 tons, track next to track); factor C (split plots) – four different soil tillage for the sowing of maize cultivated after multi-species grasslands and after winter triticale:

- TS-1 (control) skimming to 12 cm + harrowing (after the preceding crop has been harvested); pre-winter ploughing to 28 cm; cultivator + harrow + string roller (in spring before sowing);
- TS-2 (reduced tillage method) grubber 2x; rototiller (after the preceding crop has been harvested); before the sowing: 2 x passive tillage unit (cultivator + harrow + string roller);

– TS-3 (reduced tillage method) disk harrow (after the preceding crop has been harvested); pre-winter medium ploughing to 25 cm; pre-sowing tillage using a passive unit (cultivator + harrow + string roller);
– TS-4 (reduced tillage method) subsoiler to 40 cm (after the preceding crop has been harvested); pre-winter medium ploughing to 20 cm (before winter); (in spring before sowing) a passive tillage unit (harrow + string roller).

The species composition of 2-year grassland was as follows: *Medicago sativa* (36%), *Lolium perenne* (13%), *Phleum pratense* (13%), *Trifolium pratense* (11%), *Lolium multiflorum* (9%), *Lolium hybridum* (9%) and *Festulolium* spp. (9%).

Half of the field to be sown with maize cultivated after grassland and half of the field to be sown with maize cultivated after winter triticale were packed (5 ha), while the other half (5 ha) was left unpacked. On both plots with and without soil packing, the four above-mentioned soil tillage methods were applied before the sowing of maize (each on an area of 1.25 ha). On each field, four plots with an area of 30 m^2 were randomly designated, on which detailed tests were carried out. The experimental unit for tillage and compaction was the field-scale strip, whereas the 30 m^2 plots represented subsamples nested within each treatment.

Each year, maize was sown in the first 10-day period of May (7th May 2017, 5th May 2018, 3rd May 2019, 8th May 2020) at a density of 8-9 plants per 1 m^2. Before the sowing of maize, the field was fertilized with cattle slurry at 60 m^3 ha^{-1}, and mineral fertilization was applied at the following amounts of pure component (kg ha^{-1}): N – 176, P – 60, K – 90, S – 9. The maize was chemically protected against weeds. After maize emergences (BBCH 10-11), preparation Adengo 315 SC (thiencarbazone-methyl + isoxaflutole) was applied against weeds at a dose of 0.3 dcm^3 ha^{-1}.

Soil and atmospheric conditions

The experiment was conducted on Haplic Luvisol (Aric, Ochric) soil formed from loamy sand (LS) on sandy loam (SL) (IUSS Working Group WRB 2022). In its 0-20 cm layer, the soil contains 63.6% sand, 16.5% coarse silt, 16.2% fine silt and 3.7% clay. The soil is characterised by soil compaction 0.67 MPa, bulk density 1.65 g cm^{-3}, water content 14.2%, pH$_{KCl}$ 6.1, organic carbon content 10.4 g kg^{-1}, total N content of 14.2 mg kg^{-1}, available of P 6.8 g kg^{-1}, available of K 11.54 g kg^{-1}, and available of Mg content 3.96 g kg^{-1}.

The experiment was conducted in a region located at the interface between Atlantic air masses (incoming from the west) and continental air masses (incoming from the east). The mean annual air temperature is 6.5°C. In the summer months (June, July and August), it ranges from 15.5°C to 17.4°C. Spring starts in mid-April and is cool, while autumn is long and warm. The air humidity in summer ranges from 60 to 80%. The annual precipitation is 550 mm. The greatest intensity of precipitation is observed in June and July (75-95 mm). Data on the weather pattern during the study period against the mean multi-year (1962-2002) values are provided in Table 1.

Table 1

Temperature and precipitation during the maize growth period in the years 2017-2020

Years	Months						Mean/Total
	Apr	May	June	July	Aug	Sept	
	Mean air temperature °C						
2017	8.0	12.5	14.9	18.8	16.7	15.1	14.3
2018	7.8	12.6	16.1	21.1	17.3	15.8	15.1
2019	7.3	13.5	17.5	17.5	18.4	12.7	14.5
2020	7.0	12.5	16.6	18.3	17.7	11.8	14.0
1962-2002	7.0	12.6	15.1	17.2	16.8	12.6	13.6
	Precipitation mm						
2017	22.0	68.2	35.4	83.9	39.6	17.9	267.0
2018	24.2	93.2	83.5	27.1	141.7	105.6	475.3
2019	26.8	79.7	60.8	176.5	81.0	65.4	490.2
2020	33.8	48.4	27.8	47.0	103.1	17.0	277.1
1962-2002	35.4	57.6	69.5	81.6	75.2	59.1	378.4

Chemical properties of the soil

The soil for chemical analyses was collected in the spring of 2017 before the experiment was set up and again after the experiment was completed in 2020. Samples were collected using an Egner's cane, from a soil layer of 0-20 cm on each plot, at four fixed locations (at equal intervals). The following parameters were determined: soil pH (1 mole KCl), the soil organic carbon (SOC) content, the total N content, and the available forms of phosphorus, potassium and magnesium. Soil acidity was determined by the potentiometric method, and soil organic carbon was assayed by the calorimetric method through oxidation with a solution of $K_2Cr_2O_7 + H_2SO_4$, and an absorption measurement on a spectrophotometer. The total N content was determined by the Kjeldahl method, available forms of phosphorus and potassium were assayed with the Egner–Riehm method, and Mg was analysed according to the Schachtschabel method. Based on the content of C and N in the soil, the ratio of the two elements (C:N) was calculated. All analyses were carried out in a certified laboratory of the Chemical and Agricultural Station in Olsztyn, Poland.

Maize silage mass yield

The maize green matter yields from each plot, excluding the marginal strips on each side (with a width of 0.25 cm), were determined at the maize kernel development stage (BBCH 79) when the water content in the plants was 35%. The yield of green mass of maize was determined each year. The results are presented as averages over the years 2017-2020 (due to the lack of significant differences between years).

Statistical analysis

The results of the study were analysed using univariate and multivariate statistical approaches. Interactions between year and experimental treatments were tested and found to be nonsignificant (p>0.05); therefore, all results are presented as averages across the four study years. Differences in soil chemical properties between the beginning of the experiment (2017) and its completion (2020) were evaluated using a dependent (paired) t-test. Subsequently, the data collected after the completion of the experiment were subjected to further analyses. A three-factor analysis of the variance (ANOVA) of the strip-split-plot design model was used to assess the significance of the effects of the factors studied and their interactions on the studied chemical properties of the soil and the maize yield. The normality assumption was assessed using the Shapiro-Wilk test, homogeneity of variances was checked with the Levene's test, and potential outliers were identified based on standardized residuals. All variables met the assumptions of ANOVA at α=0.05. Comparisons between the control tillage system (TS1) and the reduced tillage variants (TS2, TS3, TS4) were performed using the Bonferroniadjusted *posthoc* test at α=0.05. Finally, a multivariate principal component analysis (PCA) was applied as part of a holistic summary. All analyses were conducted at a significance level α=0.05 using the Statistica 13.3 package (TIBCO Software Inc. 2017).

RESULTS

Chemical properties of the soil at the beginning and end of the study

In this study, soil packing and tillage methods differently influenced soil pH under maize following grassland and triticale (Table S1). After grassland, TS-3 significantly reduced pH in compacted plots (from 5.63 to 5.56), while no significant changes occurred in uncompacted plots. After triticale, TS-4 increased pH in uncompacted soil (from 6.00 to 6.15); no changes were observed in compacted plots.

SOC increased significantly only in uncompacted soil after grassland (TS-4) and in compacted soil after triticale (TS-2) – Table S1. Total N content rose across all treatments, with the highest values in uncompacted TS-3 and

TS-4 (grassland), and compacted TS-2 (triticale). The C:N ratio narrowed over time, especially under TS-3 after grassland.

Phosphorus content remained stable in uncompacted soil after grassland but decreased under TS-3 in compacted plots (from 75.0 to 74.1 mg kg^{-1}). After triticale, P increased under TS-3 in both compacted and uncompacted plots (e.g., from 102 to 104 mg kg^{-1}) – Table S2.

Potassium content was unaffected by tillage in uncompacted soil after grassland but increased under TS-1 in compacted plots (from 141 to 149 mg kg^{-1}). After triticale, all tillage methods increased K content, with the highest changes under TS-2 (uncompacted, +4.1%) and TS-3 (compacted, +4.3%) – Table S2.

Magnesium content increased only in compacted soil: after grassland (TS-4, from 38.9 to 39.8 mg kg^{-1}) and after triticale (TS-1 and TS-3, from 43.1 to 44.6 and 43.9 to 44.2 mg kg^{-1}, respectively). No significant Mg changes were observed in uncompacted plots under either preceding crop (Table S2).

Maize cultivation and the chemical properties of the soil, depending on the preceding crop, soil packing and soil tillage methods

The analysis of variance of the strip-split-plot design model (Table S3) showed that the experimental factors under study and their interactions had the greatest effect on the phosphorus and potassium contents in the soil and the least effect on the maize green matter yield. Regarding the main effects, the preceding crop (except SOC) had the greatest effects, followed by the tillage system (except the yield) and soil packing (except Mg and the yield).

The assessment of the main effects revealed that after 4 years of research, soil following a grassland preceding crop exhibited a significantly lower pH (5.8) compared to soil after a triticale preceding crop (6.0) – Table S4. Soil compaction was found to increase soil acidity (decrease pH). A significantly higher pH was observed with the application of the TS-2 no-tillage system (grubber 2x, rototiller (after the preceding crop has been harvested), before sowing: 2 x passive tillage unit) than with the other cultivation methods.

No significant effect of preceding crops and soil compaction on SOC was observed. However, a 4.6% higher content of this element was found in the soil under TS-3 and TS-4 tillage compared to TS-1 and TS-2. The C:N ratio was not significantly affected by the preceding crops. Its value in the compacted treatment (10.9) was significantly lower than in the non-compacted treatment (11.5). The soil following the triticale preceding crop exhibited significantly higher levels of available P, K, and Mg compared to the grassland preceding crop by 29.5%, 19.1%, and 18.4%, respectively (Table S4). Soil compaction induced an increase in K content by 32.3% and a slight decrease in P content by 1.1%, while it had no effect on Mg content. Irrespective of the preceding crop and soil compaction, the TS-4 cultivation (subsoiler to 40 cm, pre-winter medium ploughing to 20 cm, a passive tillage unit –

harrow + string roller) resulted in the highest content of total N, available P, K, and Mg, the lowest SOC, and the narrowest C:N ratio.

Figure 1 shows that nearly none of the reduced tillage systems under study (TS-2, TS-3 and TS-4) significantly differentiated the soil acidity (pH)

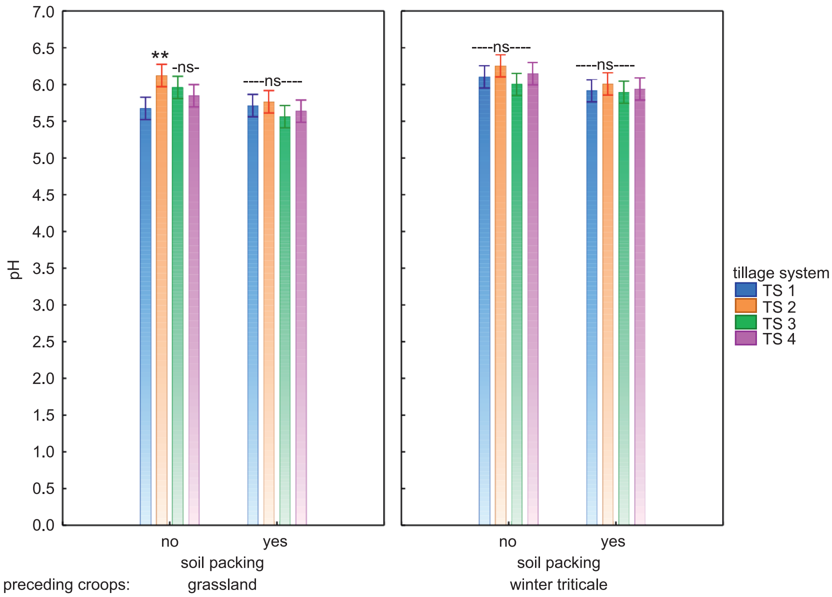

Fig. 1. The significance of the differences in the mean values of soil acidity after different tillage variants (TS 2, TS 3, and TS 4) as compared to the control plot (TS 1). The columns show mean values, and the error bars show 95% confidence intervals. * Significant at the 0.05 probability level, ** significant at the 0.01 probability level, ns – not significant.

as compared to plough tillage (TS-1, control plot), irrespective of the preceding crop and soil packing. An exception was the TS-2 tillage system (grubber, rototiller, before the sowing: 2 x passive tillage unit) in the cultivation of maize after grassland (plots without packing), after the application of which a pH value being highly significantly higher than that after the control plot (TS-1) was found.

Regarding the SOC content (Figure 2a), it was demonstrated that in the cultivation of maize after grassland, both on the plot without packing and with packing, the soil was characterized by its lower content following the application of the TS-4 tillage variant (subsoiler to 40 cm, medium ploughing to 20 cm, a passive tillage unit (harrow + string roller)), as compared to the TS-1 tillage variant. The remaining tillage system did not differentiate the SOC content significantly. However, in the cultivation of maize after triticale, the mean SOC values were at a similar level (non-significant differences).

Figure 3*a-c* shows the variability of the P, K and Mg contents in the soil under the influence of the experimental factors. In all the cases under ana-

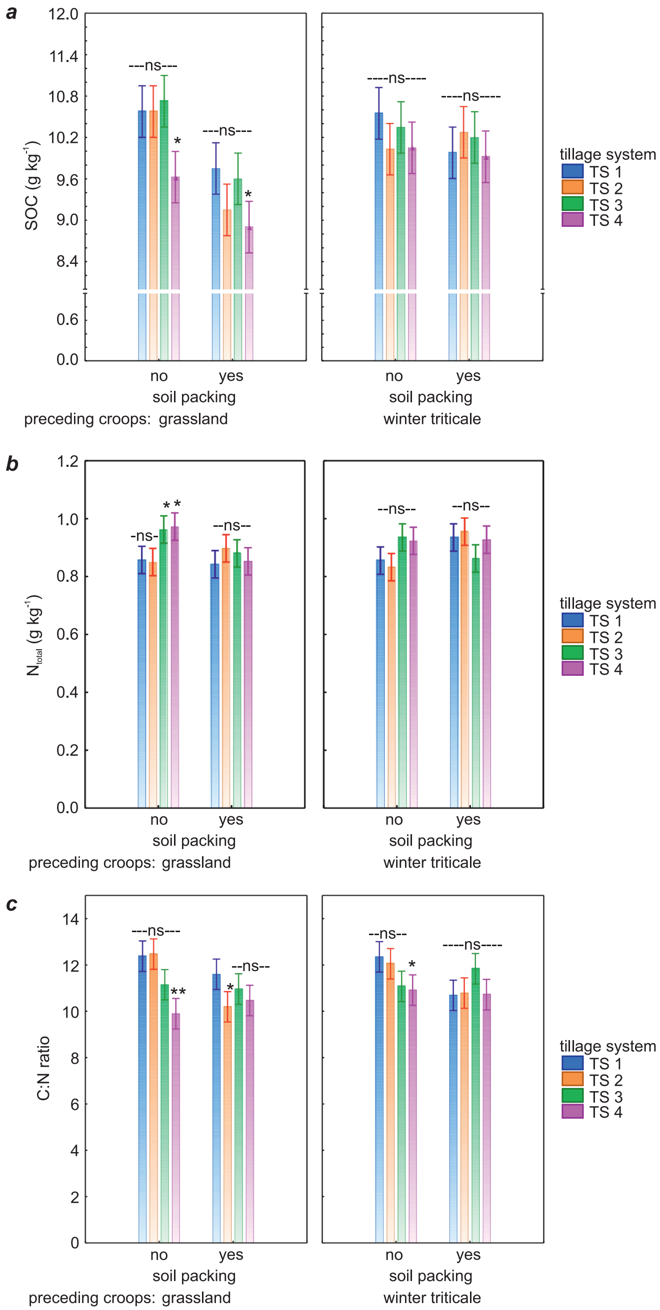

Fig. 2. The significance of the difference in the mean values of soil organic carbon content (*a*), total soil nitrogen content (*b*), and carbon to nitrogen ratio (*c*) after different tillage variants (TS-2, TS-3, and TS-4) as compared to the control plot (TS-1). The columns show mean values, and the error bars show 95% confidence intervals. * significant at the 0.05 probability level, ** significant at the 0.01 probability level, ns – not significant.

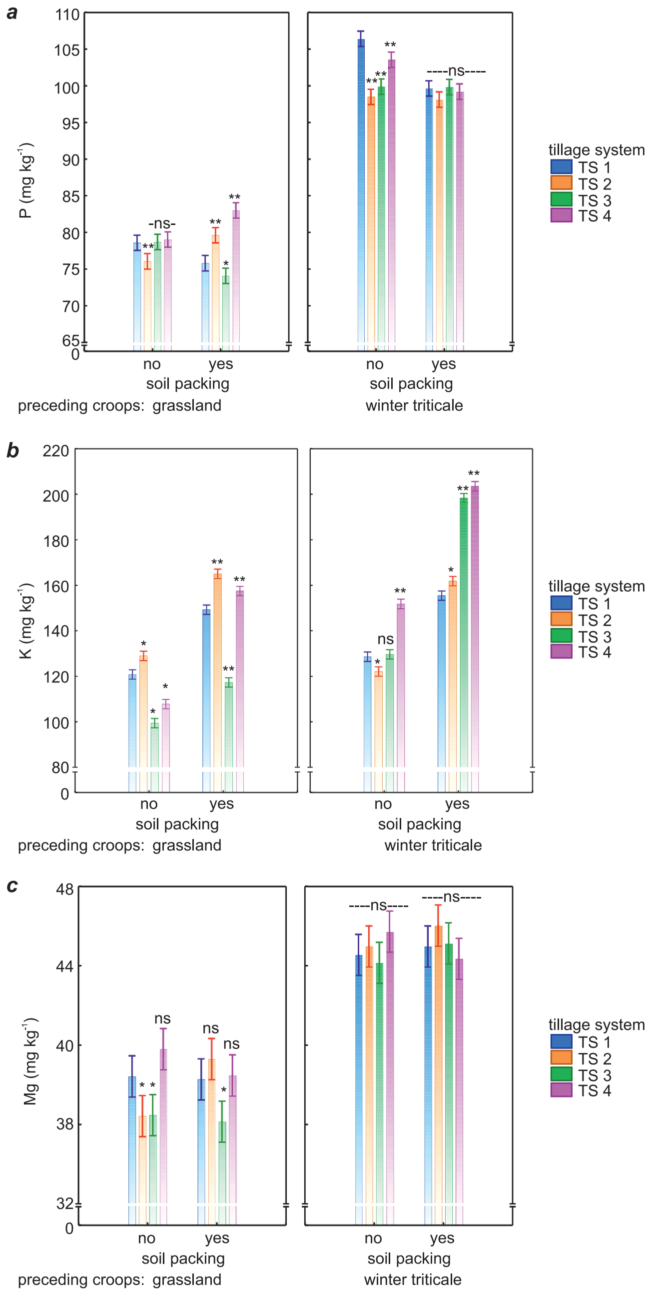

Fig. 3. The significance of the differences between the mean contents of phosphorus (*a*), potassium (*b*) and magnesium (*c*) in the soil after the application of different tillage variants (TS-2, TS-3 and TS-4) relative to the control plot (TS-1). * significant at the 0.05 probability level, ** significant at the 0.01 probability level, ns – not significant

lysis, a highly significant effect of the preceding crop was noted (Table S3). This indicates that the cultivation of maize on the field after triticale resulted in a significantly higher content of these macronutrients in the soil than the cultivation of maize after grassland. In addition, this is accompanied by the significance of the effect of the tillage system factor and its interaction with the remaining factors, which affected the P, K and Mg contents in the soil (Table S3). Although the phosphorus content in the soil was lower in the cultivation of maize after grassland than in the cultivation of maize after triticale, significant differences between the reduced tillage variants (TS-2, TS-3 and TS-4) as compared to plough tillage (TS-1) were revealed after grassland. On the plot without packing, after the application of the TS-2 reduced tillage variant, the P content was significantly lower than that after the TS-1 reduced tillage variant. On the plot with soil packing, the opposite situation was found (Figure 3*a*). After the triticale preceding crop, non-significant differences were noted in the P content in the packed soil under the influence of tillage systems. On the soil without packing, after all reduced tillage methods, a significantly lower content of this element was noted than that after plough tillage (TS-1).

In the cultivation of maize after grassland, irrespective of soil packing, the TS-2 tillage variant (grubber, rototiller, before the sowing: 2 x passive tillage unit) significantly increased the K content as compared to the TS-1 plough tillage variant, and the opposite effect was observed for the TS-3 tillage variant (disk harrow, medium ploughing to 25 cm, pre-sowing tillage using a passive unit) as compared to TS-1 (Figure 3*b*). In contrast, depending on soil packing, the TS-4 tillage variant (subsoiler to 40 cm, medium ploughing to 20 cm, a passive tillage unit (harrow + string roller) had a significantly different effect on the potassium content in the soil as compared to the TS-1 plough tillage variant (Figure 3*b*). After the grassland preceding crop, it significantly reduced the K content as compared to TS-1 on the plot without packing, whereas on the plot with packing, it resulted in its increase. The application of the TS-4 tillage variant had a different effect on the cultivation of maize after triticale. On the plot with packing and without packing, a significantly higher K content in the soil was found than after the application of the TS-1 tillage variant. The remaining tillage systems (TS-2 and TS-3) revealed a different effect determined by soil packing (Figure 3*b*).

Analysis of the variability of the magnesium content in the soil showed that significant differences only occurred in the cultivation of maize after grassland (Figure 3*c*). After this preceding crop, the application of the TS-3 tillage variant on the plots without packing and with packing, and on the plot with packing, the application of the TS-2 tillage variant resulted in a significantly lower content of this element in the soil than that after the application of TS-1. After the triticale preceding crop, no significant differences were found in the K content between the TS-2, TS-3 and TS-4 tillage variants and the TS-1 variant.

Maize yield, depending on the preceding crop, soil packing and reduced soil tillage methods

The analysis of variance showed that the maize green matter yield was significantly affected only by the preceding crop (Table S3 and S4). The average maize yield at the site after grassland amounted to approx. 70 Mg ha^{-1}, whereas after winter triticale, it was lower by 12.9% (Figure 4). Soil compaction had no significant effect on maize yield. Under a particular preceding crop, irrespective of soil packing, maize yielded a similar level after all the tillage systems under assessment (not significant differences).

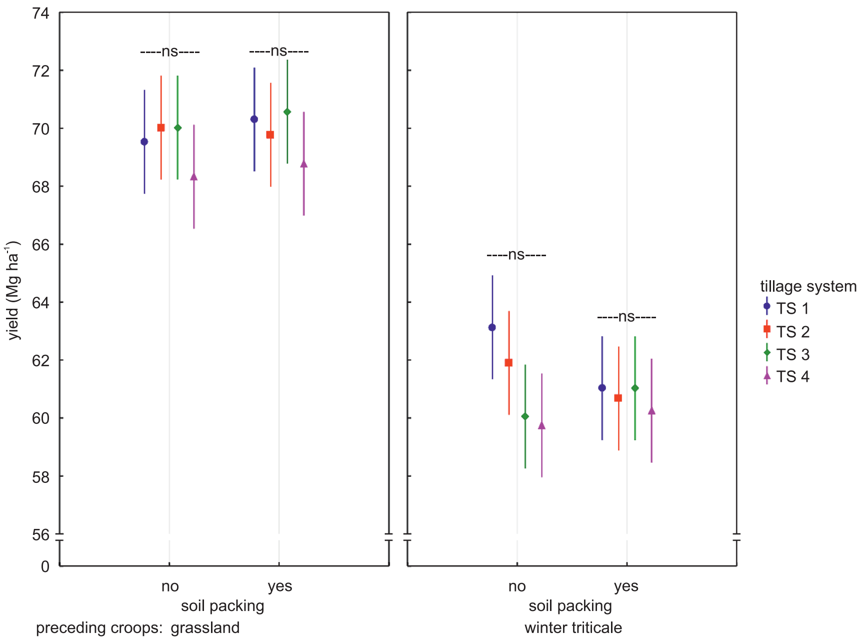

Fig. 4. The average maize yield depends on the preceding crop, soil packing and different soil tillage systems. The dots indicate the mean value, and the error bars show 95% confidence intervals; ns, not significant

Multivariate principal component analysis (PCA)

In contrast to the previous classical statistical analyses, the multivariate PCA analysis considered all the characteristics under study simultaneously (Figure 5), which offered a broader view of the obtained study results.

This analysis explained 73.8% (PC1+ PC2 = 46.6% + 27.2%) of the total variance (variability). The variability in soil acidity (pH), the P and Mg contents in the soil, and the maize yield were linked to the PC1 principal component. The second component, PC2, presented the variability in the soil organic carbon (SOC) content, C:N ratio and the potassium content in the soil. The biplot clearly indicated the separation between the experimental

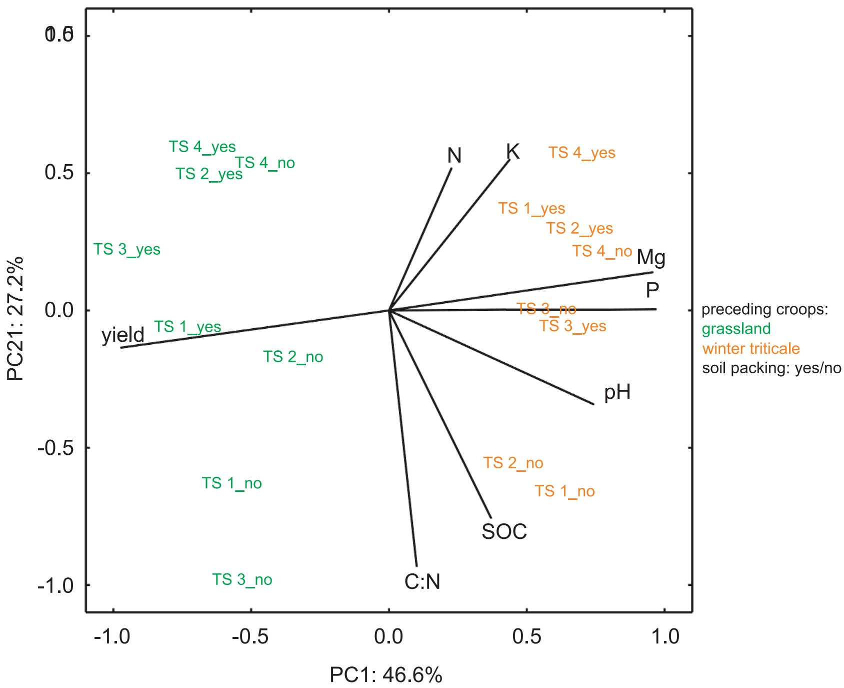

Fig. 5. Biplot of the principal component analysis (PCA)

crops cultivated after grassland and those cultivated after triticale. This confirms that irrespective of the tillage technology and soil packing, the maize yield was always greater after grassland. On the other hand, the P and Mg contents in the soil were always higher after the winter triticale previous crop, irrespective of soil packing and the tillage systems. Furthermore, these elements were strongly positively correlated with each other. The SOC, C:N and K vectors separated the plots with packing (below 0 on the PC2 axis) from those without packing (above 0 on the PC2 axis). It followed that, irrespective of the preceding crop and the tillage system, the plots without soil packing were simultaneously characterized by higher SOC content and C:N ratio with a lower potassium content. On the soil with packing, the relationship between the SOC with C:N ratio and K contents was the opposite (Figure 5). Considering all the studied chemical properties of the soil and the yield, PCA analysis revealed that in the cultivation of maize on the plots with packing after grassland, similar effects were brought about by the TS-2 and TS-4 tillage variants, whereas after triticale, by the TS-3 and TS-4 variants. On the soil without packing, it was not that obvious. However, following the cultivation after grassland, the TS-3 tillage variant stood out, whereas in the cultivation after triticale, the TS-1, TS-2 and TS-3, very similar to each other, stood out.

DISCUSSION

Consistent with our first and third hypotheses, the preceding crop emerged as the primary determinant of both soil chemical properties and maize yield, with grassland providing a clear legacy effect regardless of other management factors. The results indicate that the preceding crop significantly affected soil pH and the availability of phosphorus, potassium and magnesium, whereas its influence on SOC, total nitrogen and the C:N ratio was limited when considered as a main effect, which is consistent with earlier reports on short-term rotation effects on soil nutrients (Liebig et al. 2002, Plaza-Bonilla et al. 2013). Higher pH and higher contents of available macronutrients after winter triticale are consistent with studies showing that cereal-based systems may leave higher residual nutrient levels in soil.

Despite the high biomass input associated with the grassland preceding crop, no pronounced increase in SOC or total nitrogen was detected during the study period, which agrees with studies indicating that measurable SOC accumulation often requires longer time spans (West, Post 2002, Poeplau, Don 2015). This suggests that changes in soil organic matter pools require longer time spans to become measurable. Similar results have been reported in studies demonstrating that short- to medium-term experiments often fail to capture significant SOC accumulation following grassland conversion.

Maize silage yield was higher after grassland than after triticale, despite lower soil pH and lower macronutrient availability. This indicates that yield formation was not directly related to the measured nutrient concentrations alone. However, potential mechanisms involving soil biological or physical improvements remain speculative, as they were not directly quantified.

Soil compaction led to slight changes in selected chemical properties, including a decrease in pH and SOC and an increase in available potassium, in line with previous observations under moderate compaction levels (Hamza, Anderson 2005, Batey 2009). It should be emphasized that penetration resistance values indicated relatively mild compaction. Consequently, the observed effects on nutrient availability were limited and should not be extrapolated to conditions of severe soil compaction. The modest response of soil chemical indicators is consistent with reports showing that element redistribution under compaction depends strongly on compaction intensity.

Regarding our second hypothesis, the impact of tillage systems (TS-1 to TS-4) on soil properties was found to be significant but highly dependent on the interactions with compaction and the preceding crop type, as evidenced by the ANOVA results. The effects of tillage systems on soil chemical properties were primarily expressed through interactions with preceding crop and soil compaction, as also reported in long-term tillage experiments focusing on nutrient stratification and SOC dynamics (Six et al. 2002, Blanco-Canqui, Lal 2008). Reduced tillage did not consistently alter pH or nutrient availability when considered as a main factor. However, under specific conditions, reduced tillage contributed to slightly higher SOC and total nitrogen contents, particularly following winter triticale under compacted soil conditions. These results suggest that reduced tillage may support the preservation of selected soil elements, although the magnitude of changes was small. No clear tillage effect on maize yield was observed, indicating that short-term changes in soil chemical properties were insufficient to translate into yield responses within the duration of the experiment. In summary, preceding crops exerted a stronger influence on soil chemical properties and maize yield than tillage system or mild soil compaction. The effects of tillage and compaction were mainly evident through interaction terms rather than as independent factors. These findings underline the importance of integrated management approaches and long-term field studies for understanding element dynamics in agricultural soils.

The multivariate PCA analysis complemented the univariate statistical results by providing an integrated overview of the relationships among soil chemical properties and maize yield. The first principal component (PC1) was mainly associated with soil pH, the availability of phosphorus and magnesium, and maize yield, indicating a coordinated response of these variables primarily driven by the preceding crop (Abdi, Williams 2010, Plaza-Bonilla et al. 2013). In contrast, the second principal component (PC2) was related mainly to soil organic carbon content, the C:N ratio and potassium availability, reflecting differences associated with soil packing (Six et al. 2000). The contrasting behaviour of SOC and potassium suggests that potassium availability was more sensitive to soil physical constraints than phosphorus and magnesium, which is consistent with the results of the univariate analyses (Blanco-Canqui, Lal 2008). Overall, the PCA supported the conclusion that preceding crops exerted a stronger influence on soil chemical properties than tillage system or soil compaction, while also highlighting element-specific responses to soil management practices.

CONCLUSIONS

The findings of this study indicate that the role of preceding crops in shaping soil chemical conditions should be considered a key component of nutrient management strategies in maize-based cropping systems. In contrast, the influence of tillage system and soil compaction on soil chemical properties appears to be more context-dependent and strongly mediated by interactions with crop rotation rather than by their independent effects. The limited response of soil chemical indicators to compaction highlights the importance of considering compaction intensity when interpreting its potential impact on soil fertility. Differences in maize silage yield between preceding crops suggest that crop performance cannot be explained solely by the measured nutrient concentrations, emphasizing the need to account for integrated soil processes when evaluating management practices. Ultimately, the results of this study allow for the full acceptance of the formulated hypotheses, demonstrating that in on-farm conditions, biological factors (preceding crops) play a superior role in shaping soil fertility and crop performance compared to technical interventions like tillage or moderate compaction. These findings underline the importance of combined management approaches and long-term field studies for improving assessments of soil fertility and nutrient dynamics under practical farming conditions.

Author contributions

Conceptualization – K.O., M.W., methodology – K.O., software – D.Z., validation – K.O., M.W. and D.Z., formal analysis – D.Z., investigation – K.O., resources – K.O., data curation – D.Z., writing – original draft preparation – K.O., M.W. and D.Z., writing – review and editing – K.O., M.W. and D.Z., visualization – D.Z., supervision – K.O. and M.W., project administration – K.O. and M.W., funding acquisition – K.O. and D.Z.

Conflicts of interest

The authors declare no conflicts of interest.

Supplementary material

The manuscript contains supplementary material available only online: https://jsite.uwm.edu.pl/articles/view/3656/

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