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Assessment of the effect of intensive agricultural production on nutrient movement in soil

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Abstract

The objective of the paper was to investigate the abundance of available forms of macroelements in the subsoil on land under intensive use, and to assess whether deeper soil layers can serve a function in the nutrition of crops. Samples were collected for layers: 0–25, 26–50, and 51–75 cm from 8 boreholes with a diameter of 20 cm, whereas samples were collected from opposite walls of two of them. The pH value of all collected samples and the content of available forms of macronutrients: mineral nitrogen, phosphorus, potassium, magnesium and calcium were examined. Then the mean content of nutrients was compared by each layer. The Mehlich-3 method was used for the extraction of P, K, Mg and Ca, then the content was determined by the atomic absorption spectrometry (AAS) method. The spectrophotometric measurement of mineral nitrogen was made using a Solar flow analyzer with a cadmium column. Nitrogen extraction was performed from dry soil using a 1% K_2SO_4 solution in a soil-solution ratio of 1:10. In the statistical analysis, the average contents of components and pH in individual layers were compared using Tukey's test (p=0.05). The obtained results show a trend for transport down the soil profile of phosphorus, calcium, and magnesium. The study evidences that the application of mineral fertilisers increases the abundance of nutrients in soils at the analysed depths, and crop rotation should involve deep-rooting crops that can efficiently use the subsoil as a source of nutrients. Proper arrangement of crop rotation with deep-rooting species can contribute to a reduction of leaching of nutrients. This should translate into more efficient use of fertilisers, and therefore less dispersal of nutrients in the environment, as well as increased economic benefits.

1. Introduction

The implementation of the concept of sustainable development in agriculture requires rational use of resources (United Nations Development Programme, 2015). One of the current challenges in agriculture is the concept of sustainable intensification assuming "the improvement of total productivity of agriculture through greater efficiency of use of resources and reduction of the environmental impact per production unit" (Czyżewski and Staniszewski, 2018; Lampkin et al., 2015).

Research on more detailed determination of the distribution of nutrients in soil profiles may allow for more accurate selection of fertiliser doses, and more detailed preparation of the nutrient budget (Pietrzak, 2013). According to the guidelines of the Mazowsze Centre of Agricultural Consultancy (MODR, 2022), samples for the analysis of abundance of P, K, Mg, and pH should be selected for the topsoil at a depth of 0–20 cm and 0–60 cm or 0–90 cm for nitrogen. Depth may not sufficiently reflect the amounts of available forms of nutrients, particularly for deep-rooting plants, e.g. those from the legume or mustards family. Leaching of nutrients from the shallowest layer causes their transport deeper from where they can be absorbed by the root system and transported to the topsoil with biomass. Moreover species like a rapeseed and black mustard with strong taproot may alleviate soil compaction, what makes subsoil more suitable for other crops with shorter and more distracted roots (Costa and Coitinho, 2022).

The application of mineral fertilisers is necessary for obtaining high yields of good quality. The awareness of the exhaustion of deposits of raw materials for the production of fertilisers encourages research on their better use. Particular attention should be paid to phosphates the resources of which are estimated to run out in 30–40 years (Cordell et al., 2012).

The issue of transport of nutrients in soil profiles has both the environmental and economic aspect. On the one hand, nutrients stimulate plant development. On the other hand, they can be a source of environmental pollution. It is important to undertake activities aimed at fertilisation optimisation (Podleśna, 2019). The phenomenon is particularly magnified in commercial farms with intensive crop production, where mineral fertilisers are applied in high doses. The dynamics of nutrient transport are affected by among others: the amount and intensity of atmospheric precipitation, grain size composition of the soil, and plants inhabiting the soil (Kopeć, 2007). The dependency of the transport dynamics on the aforementioned and other factors points to the need of further research in the scope.

The aim of the study is to answer the question to what degree nutrients available in the subsoil at 26–75 cm should be considered in the fertiliser dose. Knowledge on the dynamics of particular elements and their abundance in soil in the 0–75 cm profile will permit the preparation of a more detailed nutrient budget, and crop rotation taking into account deep-rooting crops.

2. Materials and methods

2.1. Study area

The subject of the study are soil profiles up to a depth of 75 cm in an arable field subject to intensive mineral fertilisation. Samples were collected from an individual farm in the Warmińsko-Mazurskie Voivodeship, in the Kętrzyn District, Srokowo Commune (GPS coordinates 54.218598, 21.447369). No deep-rooting legume crops have been applied in the sampled field for many years. The crop rotation covered winter wheat, winter triticale, spring barley, and winter rape.

The soils in the analysed field are included to soil quality classes IIIa, IIIb, and IVa. Light dusty loam and medium dusty loam occurs over a major part of the field. No organic fertilisation has been applied in recent years. In the field subject to sampling, the same farming methods and the same mineral fertilisation have been applied:

- $CaCO_3$ in a dose of 1.5 t ha^{-1} (08.2019)
- NPK (8-20-30) in a dose of 250 kg ha^{-1} (29.08.2020)
- RSM (32%) in a dose of 200 l ha^{-1} (84 kg N) (10.03.2021)
- RSM (32%) in a dose of 200 l ha^{-1} (84 kg N) (16.04.2021)
- Ammonium nitrate in a dose of 150 kg ha^{-1} (51 kg N) (08.06.2021)

The samples were collected from three soil layers: 0–25 cm, 26–50 cm, 51–75 cm. Boreholes were performed by means of a soil corer with a diameter of 25 cm at a depth of 75 cm, followed by sample collection from the walls of the boreholes of particular layers.

A total of 60 samples were collected from 8 boreholes. Samples from boreholes No. 6 and No. 8 were collected twice, from opposite walls of the boreholes. A total of 20 samples were collected for each soil layer. Smaller samples were collected for a separate analysis of nitrogen content. Those samples were subject to freezing.

2.2. Analytical methods

For the determination of P, K, Mg, Ca, and pH, the soil was dried to air-dry state, and then sieved through 2 mm mesh. The samples were collected on 20 March 2022 from the field before the application of fertilisers and sawing of spring crops.

Mineral nitrogen content was analysed by means of the flow injection colorimetric method. Spectrophotometric measurement of mineral and nitrate nitrogen was performed by means of a Solar flow analyser with a cadmium column. Extraction was conducted on wet soil in 1% K_2SO_4 solution with a soil-solution ratio of 1:10, during one-hour shaking.

The remaining macroelements (K, Mg, Ca) were determined by means of the Mehlich-3 method (Ziadi and Tran, 2008; Kęsik et al., 2015; Korzeniowska et al., 2019). The extraction employed concentrated Mehlich-3 extraction solution then the content was determined by the atomic absorption spectrometry (AAS) method (Żyrnicki et al., 2010) Phosphorus was determined colorimetrically by means of the vanadium method (in yellow).

The soil reaction was analysed by means of the potentiometric method after extraction in KCl solution with a concentration of 1 mol dm^{-3}.

In the statistical analysis, the average contents of components and pH in individual layers were compared using Tukey's test (p=0.05).

3. Study results and discussion

The obtained results show that nutrients can differ significantly in the dynamics of mutual movement (Figs. 1–5). Soil is characterised by spatial variability (Niedźwiecki et al., 2015), collectively determined by biological, physical, and chemical factors (Panday et al., 2019). In a soil profile, vertical transport of nutrients is caused by plants through their incorporation into the plant biomass and their transport upwards, as well as abiotic forces related to their leaching down the profile (Jobbagy and Jackson, 2001). Considerable variability is also observed in own results. It is particularly evident in results of contents of available forms of potassium in samples No. 8 and 9 at a depth of 0–25 cm (Fig. 3.) and calcium content at a depth of 51–75 cm (Fig. 5.). Samples No. 6 and 7 as well as 8 and 9 were collected in pairs from the same boreholes, from walls on opposite sides. They were therefore located at a distance of 20 cm from each other. Despite a small distance between the sampling points, their results show significant differences.

3.1. Nitrogen

In the literature, nitrogen in soil is commonly considered a mobile element, easily transported down the soil profile (Lipiński 2019). At the same time, the topsoil shows the highest nitrogen concentration (Gorlach and Grzywnowicz, 1989; Jobbagy and Jackson, 2001), as also evidenced by results of own research. Mean mineral nitrogen content in the layer 0–25 cm reached 24.54 mg kg soil^{-1}, and the coefficient of variation (CV) 24%. The maximum concentration of mineral nitrogen in the study reached 42.73 mg N_{min} kg soil^{-1}, and the minimum 12.86 mg N_{min} kg soil^{-1} (Fig. 1). Mean nitrogen content in all samples reached 22.57 mg N_{min} kg soil^{-1}. The obtained results showed that with an increase in depth, the content of both forms of nitrogen decreases (NH_4^+ and NO_3^-). The difference between

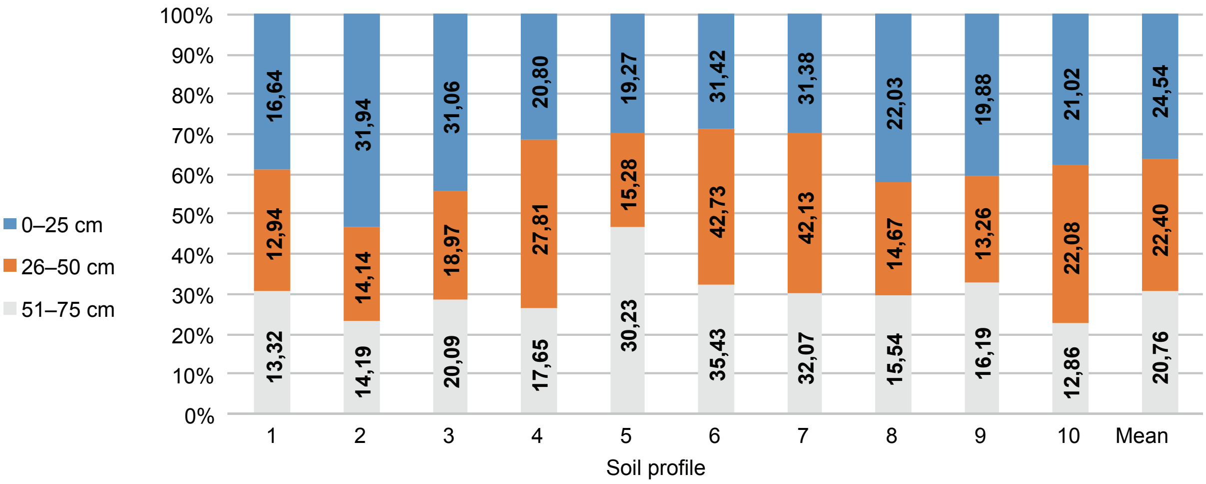

Fig. 1. Share of mineral nitrogen in the tested soil profiles

mean mineral nitrogen content of the first and second layer is 2.14 mg kg soil^{-1}, i.e. it is lower by 8.7%. The share of nitrogen content in particular layers (Fig 1.) shows that deeper layers can be important for nutrition of deep-rooting crops. Research conducted in Germany (Heinemann and Schmidhalter, 2021) showed a decrease in the content of mineral nitrogen, and an increase in CV with an increase in depth of sample collection. Similar results were obtained in own research (Table 1.). The study results show that nitrogen content decreases with an increase in depth, although in each layer the results are approximate and show no significant differences. This shows that such high saturation of deeper layers with nitrogen may play a role in nutrition of crops with an adequate root system.

3.2. Phosphorus

Phosphorus contents in all the analysed samples were classified from very low to medium class of available phosphorus content determined by means of the Mehlich 3 method (Fotyma et al., 2015) (Fig. 2). Phosphorus contents, like those for nitrogen, were the highest in layer 0–25 cm (Table 1., Fig. 2). The obtained results confirm that phosphorus accumulates in the soil primarily in the layer to which it is supplied (Podleśna, 2019; Jobaggy and Jackson, 2001). Similar results were obtained by Stępień and Mercik (1999). Research conducted in Olsztyn (Bartoszewicz and Karp, 2010) shows that in the case of application of mineral fertilisers (NPK), the highest phosphorus desorption

Table 1
Average nutrient content and pH in individual soil layer

Depth	Sum Nmin mg·kg soil^{-1}		mg P·kg soil^{-1}		pH (KCl)		mg K·kg soil^{-1}		mg Mg·kg soil^{-1}		mg Ca·kg soil^{-1}	
0–25	24,54	a	49,05	a	5,03	a	278,21	b	148,90	a	217,79	a
25–50	22,40	a	23,65	a	5,18	a	155,36	a	183,66	ab	197,67	a
50–75	20,76	a	36,62	a	5,93	b	121,16	a	208,92	b	272,81	a

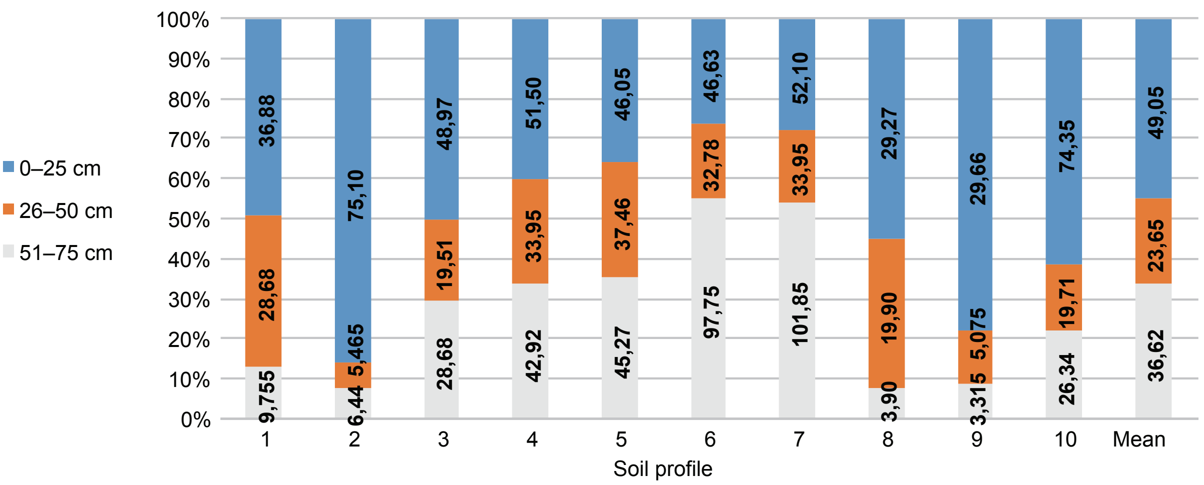

Fig. 2. Share of available phosphorus in the tested soil profiles

occurs in layers 0–25 cm and 26–50 cm, leading to an increase in its abundance in layer 51–75 cm. Own results point to the same trend. The maximum content of available phosphorus in the samples analysed in this paper was 101.85 mg P kg soil^{-1}, and the minimum 3.32 mg P kg soil^{-1} (Fig. 2). Mean phosphorus content in all samples reached 36.44 mg P kg soil^{-1}. The average content in layer 26–50 cm was 25.40 mg P kg soil^{-1} (–51.8%) lower than the average content in layer 0–25 cm. Comparable results were obtained in Chinese research (Khan et al., 2019), where the top layer of soil was the most abundant in phosphorus. Mean phosphorus content in research from Yangling in layer 0–20 cm reached 117 mg P kg soil^{-1}, and in deeper layers 20–300 cm mean content was 11.1 mg P kg soil^{-1}. Own research, however, showed an increase of phosphorus content in soil layer 51–75 cm in comparison to 26–50 cm by 12.97 mg P kg soil^{-1} (+54.8%). The obtained results are also characterised by strong variance among all samples (68.7%). The greatest divergence between content values occurs in the deepest layer, where the coefficient of variance reaches 94.9%. The availability of phosphorus depends on many factors, including microbiological processes, content of soil organic matter, pH, and C:P ratio (Podleśna, 2019). Samples with determined high phosphorus contents in layer 51–75 cm are particularly intriguing due to the limited microbiological life and content of organic matter at such depth. The obtained results do not allow for a direct assessment whether deeper soil layers can play a significant role in nutrition of crops with a deep root system. Further research in the scope is required to determine the role of phosphorus in deeper soil layers.

3.3. Potassium

Potassium content in the analysed samples decreased with depth. In layer 0–25 cm, its mean content from the collected samples was classified to the high class of abundance, in layer 26–50 cm to low class, and in layer 51–75 cm to very low class of abundance. Potassium is a nutrient with high mobility in the soil profile. Its supply to the topsoil can also contribute to an increase in its content in deeper soil layers (Stępień and Mercik, 1999). Long-term research conducted at the Experimental Station of Marian Górski in Skierniewice evidenced that in the case of application of mineral fertilisation with potassium, its accumulation increases with depth (Stępień and Mercik, 1999). Own results showed the opposite trend. American research shows that the highest accumulation of available forms of potassium occurs in the surface layer of soil (Jobbagy and Jackson, 2001).

Despite a decrease in the abundance of potassium in deeper layers, its contents can still play a substantial role in crop nutrition. Potassium content in samples from layers 26–50 cm and 51–75 cm show 15.6% and 16.8% variance, respectively. The value is very low, and the mean values show no significant differences. A significant difference is observed, however, between the shallowest layer and the remaining ones. Leaching of potassium can be associated with high concentration of calcium ions (Jalali and Rowell, 2003).

The availability of potassium in layer 0–25 cm averages 278.21 mg kg soil^{-1}, and in layer 26–75 cm 276.52 mg kg soil^{-1} (Fig. 3). Potassium content in layer 26–75 cm can play a significant role in nutrition of crops, if they have an adequately deep root system. According to Argentinian research (Correndo et al., 2021), plants are able to use potassium contained in the subsoil, particularly in the case of application of simplified farming, where straw is not mixed with the surface soil layer. According to research by Kuhlmann, spring wheat can uptake potassium from a depth greater than 30 cm, depending on the abundance of the topsoil, therefore meeting an average of 34% of demand for potassium (from 9% to 70%) (Kuhlmann, 1990). Research on soya (Maciel de Oliveira et al., 2020) showed uptake of 25% of potassium from a depth of 30 cm, and 15% from a depth of 60 cm. It is related to the root mass of soya, constituting 67% up to 30 cm, with the total length reaching up to 1.56 m (Raziel et al., 2018).

Potassium content in deeper layers can be used even in the case of farming of crops commonly considered as having a relatively shallow root system. For crops with a longer root system, the use of potassium from the subsoil should be of even more importance.

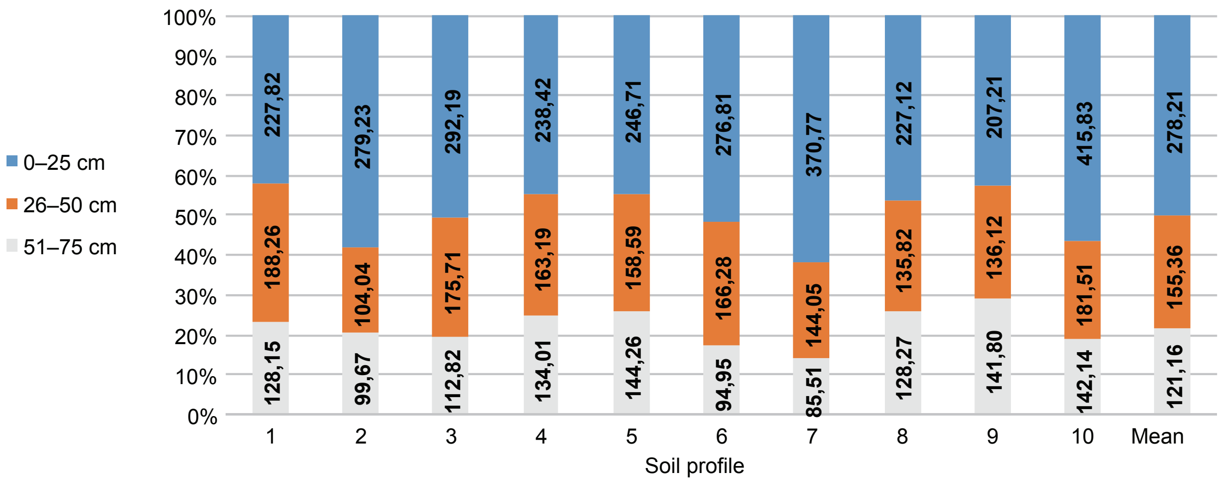

Fig. 3. Share of available potassium in the tested soil profiles

3.4. Magnesium

Magnesium contents in the analysed samples can be considered uniform. Weak variance was determined for each layer. The lowest values were recorded in the shallowest layer (from 107.10 to 185.23 mg Mg kg soil^{-1}), where all samples were classified in the medium and high class of abundance (Fig. 4). With an increase in depth, magnesium content in the analysed samples increased. Similar results were obtained by Jobbagy and Jackson (2001).

Magnesium is included to elements highly mobile in the soil environment (Gransee and Führs, 2013; Chowaniak et al. 2016), as also evidenced by its highest accumulation in the deepest of the analysed soil layers in own research. In the deepest layer 51–75 cm, mean magnesium content reached 205.85 mg kg of soil^{-1}, accounting for an average of 38.7% of available magnesium in the soil profiles. The deepest layer also showed the highest variance coefficient (23.3%) among the analysed layers, although it is weak variance. Two deeper layers (26–75 cm) accounted for an average of 72.6% of magnesium abundance in the analysed soil profiles. The research was conducted on heavy soil (light dusty loam, medium dusty loam), where the dust and silt fractions are of high importance in the context of high magnesium content (Gransee and Führs, 2013; Orzechowski and Smólczyński, 2010). The Warminsko-Mazurskie Voivodeship has the highest share of total samples in the high and very high class of magnesium content in Poland (25% and 29%, respectively) and the lowest share of samples in the very low abundance class. Only 4% of samples in the aforementioned study was qualified to very low abundance class, and 13% to low class (GUS, 2020). The relatively high magnesium abundance in the analysed soil may result from natural conditions, because no magnesium lime had been applied in the analysed field in previous years.

The decision on the manner of use of magnesium and sampling depth is a challenge involving the accurate determination of the amount of the element that crops can use (Gransee and Führs, 2013). Contents obtained in own research point to higher magnesium contents in deeper layers, suggesting that in the case of cultivation of appropriate crops, deeper layers can constitute the source of the element.

3.5. Calcium

Calcium is largely subject to leaching in the soil profile, and is easily transported down the profile (Gransee and Führs, 2013; Chowaniak et al., 2016; Kępka, 1968). Own research showed the highest calcium accumulation in the soil layer at a depth of 51–75 cm (Table 1). Similar results were obtained by Prof. Kepka (1968). At a depth of 70–80 cm, calcium contents were considerably higher than in the intermediate layers. This suggests transport of the element down the soil profile.

The surface layer is characterised by higher average content of elements (217.79 mg kg soil^{-1}) than layer 26–50 cm (197.68 mg kg soil^{-1}), although the differences are not statistically significant. The highest variance was recorded in the deepest layer (64.2%), and the lowest in the intermediate layer 26–50 cm (19.9%). It can therefore be presumed that an increase in the content of the element is accompanied by an increase in variance between contents in samples. The range of calcium content in the analysed samples is from 122.24 mg kg soil^{-1} to 396.52 mg kg soil^{-1}.

The deepest layer accounts for an average of 39.6% of available calcium in the soil profile (Fig. 5). Such a share can constitute a considerable source of nutrition for crops with adequate roots (Dijkstra and Smits, 2002). Research conducted in the Olsztyn centre (Grzegorczyk et al., 2013) shows that in mineral soils, the application of relevant crop species may contribute to a decrease in leaching of calcium through high uptake of the element by plants. At the same time, dicotyledon plants abundantly absorbing calcium and magnesium were characterised by lower uptake of potassium.

Higher Ca content in layer 0–25 cm than in layer 26–50 cm may result from regular fertilisation with the element in high doses. The criterion that should be considered in liming is the demand of crops for calcium. The greatest demand is observed in plants from the legume and mustard families. Active uptake of calcium by roots occurs only in the root apices with active

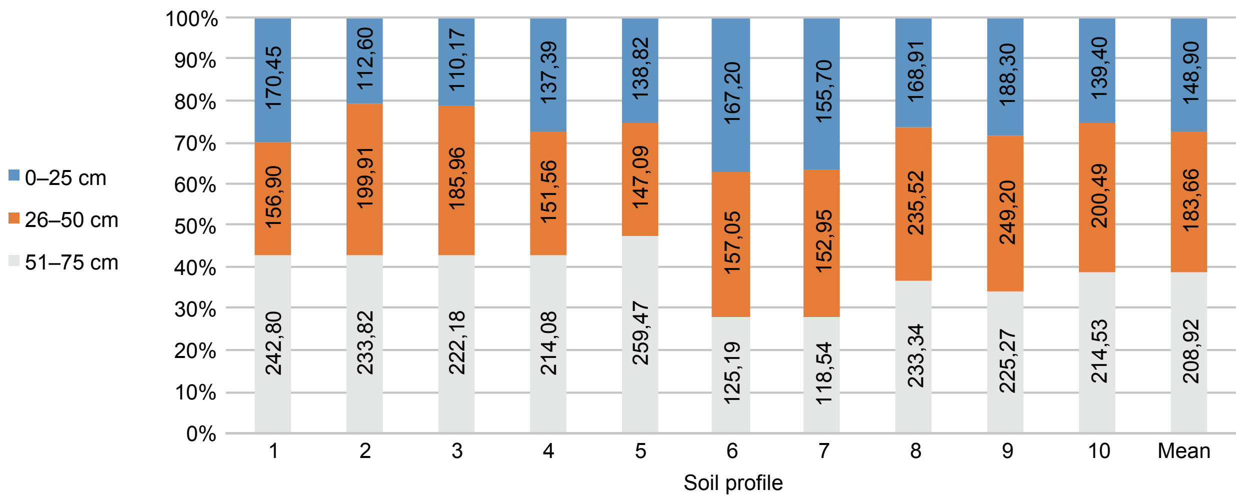

Fig. 4. Share of available magnesium in the tested soil profiles

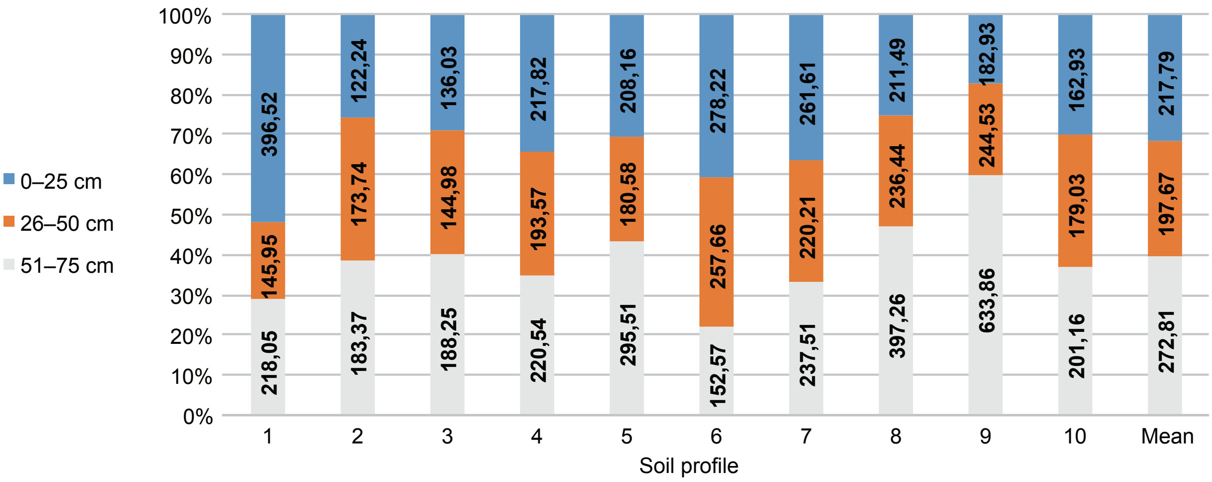

Fig. 5. Share of available calcium in the tested soil profiles

endoderm (Grzebisz et al., 2006). This additionally supports the application of deeply-rooting plants in crop rotation for an increase in the uptake of elements from deeper soil layers.

4. Conclusions

1. The subsoil can play an important role of macroelement nutrition of crops.
2. The application of mineral fertilisers increases the content of available forms of macroelements both in the surface soil layer and in the subsoil.Trends in transport of phosphorus, magnesium, and calcium in the soil profile were observed.
3. Crop rotation should involve the application of deeply-rooting crops to transport the elements back to the topsoil with biomass.
4. In the case of high abundance of available forms of nutrients in soils, intercrops should be applied. It should translate into a reduction of leaching of macroelements.

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Ocena wpływu intensywnej produkcji rolnej na przemieszczanie się składników pokarmowych w glebie

Słowa kluczowe

Wymywanie składników pokarmowych
Strefa Korzeniowa
Profil glebowy
Zasobność warstwy podornej
Makroelementy

Streszczenie

Praca miała na celu zbadanie zasobności warstwy podornej w przyswajalne formy makroelementów na gruntach użytkowanych intensywnie oraz ocenę czy głębsze warstwy gleby mogą pełnić rolę w odżywianiu roślin. Porównano zawartości składników pokarmowych w warstwach 0–25, 26–50, 51–75 cm dla 8 odwiertów o średnicy 20 cm, przy czym z dwóch próbki pobrano z przeciwnych ścian. Zbadano wartość pH wszystkich zebranych próbek oraz zawartość dostępnych form makroskładników: azotu mineralnego, fosforu, potasu, magnezu i wapnia. Do ekstrakcji P, K, Mg i Ca użyto metody Mehlich-3, następnie zawartość zbadano metodą atomowej spektrometrii absorpcyjnej (ASA). Pomiaru spektrofotometrycznego azotu mineralnego dokonano przy użyciu analizatora przepływowego Solar z kolumną kadmową. Ekstrakcji azotu dokonano z gleby suchej przy użyciu 1% roztworu K_2SO_4 w stosunku gleba- roztwór jak 1:10. W analizie statystycznej porównano średnie zawartości składników i pH dla poszczególnych warstw testem Tukeya. Otrzymane wyniki wykazują tendencje przemieszczania się w głąb profilu glebowego fosforu, wapnia i magnezu. Wykazano, że stosowanie nawozów mineralnych zwiększa zasobność gleb w składniki pokarmowe na badanych głębokościach i należy stosować w płodozmianie rośliny głęboko korzeniące się, które efektywnie mogą korzystać z warstwy podornej jako źródła składników pokarmowych. Odpowiednie ułożenie płodozmianu z gatunkami o głębokim systemie korzeniowym przyczynić się może do ograniczenia wymycia składników pokarmowych. Powinno to przełożyć się na efektywniejsze wykorzystanie nawozów, a tym samym mniejsze rozproszenie składników biogennych w środowisku i korzyści ekonomiczne.