The impact of cover crops and foliar application of micronutrients on accumulation of macronutrients in potato tubers at technological maturity stage

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Summary

The aim of the study was to assess the effect of mineral fertilization (NPK) in combination with manure and stubble crops (white mustard, pea, phacelia) and foliar application of micronutrients on the content and accumulation of macro-elements (N, P, K, Mg and Ca) in potato tubers at the of stage technological maturity. The tested plant was a potato cultivar 'Bila'. The experiment was carried out in 2010–2012, at the Wierzbucinek Research Station of the Bydgoszcz University of Technology and Life Sciences. The experimental factors were (I) fertilizer variants ($n=5$): the control (NPK), NPK + manure (FYM + NPK), NPK + white mustard (NPK + WM), NPK + pea (NPK + P), NPK + blue phacelia (NPK + PH), and (II) foliar fertilization with micronutrients ($n=2$): no fertilization with microelements (M0) and applications of fertilizer (M1). Micronutrients were applied twice a vegetation season in the form of a chelated fertilizer. The content and accumulation of nutrients in potato tubers at the stage of technological maturity were analyzed. It was found that the applied mineral NPK fertilization (the control), when in combination manure treatment and the three intercrops, significantly differentiated the content of all the studied nutrients in potato tubers. The highest concentration of nitrogen and calcium in tubers was found in the control plants, while highest concentrations of P, K and Mg were observed in tubers grown after manure application. Significantly higher nitrogen content (exclusive of 2011) as well as that of phosphorus were observed in the treatments with no foliar fertilization. In the case of magnesium and calcium, the relationship was reversed (exclusive of Ca content recorded in 2010). The experimental factors significantly differentiated the uptake values of all the nutrients analyzed and, irrespective of the study year, the largest accumulation of nutrients in potato tubers was found in the experimental variant with manure and micronutrient fertilizer application. The highest uptake of nutrients was recorded in tubers grown after pea intercrop as compared with other two intercrops tested. The correlation analysis as regards tuber yields, dry mass and starch as well as the total accumulation of nutrients, showed that regardless of the experimental variant analyzed, there was a highly

Significance of this study

What is already known on this subject?

- Potatoes belong to the group of plants positively reacting to manure fertilization. In Poland, increasing intensification of plant production, cultivation simplifications, as well as the absence of additional sources of organic matter have detrimental effects on organic matter balance in the soil and result in micronutrient deficiency. Considering the above, studies have been undertaken in search for organic matter sources alternative to manure, such as for example cultivation of stubble intercrops.

What are the new findings?

- Cultivation of intercrops, such as peas or phacelia, in combination with application of micronutrients under mineral fertilization conditions can guarantee the achievement of analogous yields of potato tubers with alike chemical composition when compared to those obtained in traditional cultivation with manure fertilization.

What is the expected impact on horticulture?

- In cultivation of root vegetables, intercrops combined with foliar application of microelements can be an alternative source of long-lasting organic matter and stabilize yields with better quality parameters as compared to those obtained from traditional field cultivation with the use of manure as a fertilizer.

significant correlation between yield/starch content and uptake of all the macronutrients under the study. Accordingly, intercropping may be an alternative to manure in potato fertilization as it does not require large expenditure, and constitutes the source of macronutrients and organic matter, as well as improves soil structure and prevents its degradation.

Keywords

chemical composition, farmyard manure, green manure, macronutrients acquisition

Introduction

The chemical composition of potato tubers is shaped by a number of environmental and agrotechnical factors, with key roles played by water as well as mineral and organic fertilization (Pehrson et al., 2010; Daccache et al., 2011). The quantity of mineral nutrients accumulated in the plant is the basis for designing the appropriate fertilization technology for cultivation of a given plant (Neeteson, 1989; Fageria, 2007b). Manure is a basic natural fertilizer in traditional potato cultivation (Makaraviciute, 2003). In many countries, including Poland, intensive research has been conducted on alternative sources of organic matter (Vos and Van der Putten, 2000; Mazur and Ciećko, 2000; Nett et al., 2011). Potato cultivation leads to significant losses of domestic resources of organic matter in the soil, therefore, it has to be naturally and organically fertilized prior to planting (Davenport et al., 2005). The cultivation of green fertilizers, to be left on the field during the autumn and winter seasons, as well as cultivation of stubble intercrops constitute an effective method of compensating for organic matter shortages in soils. If green manure catch crops are incorporated into the soil in the late autumn or the spring, nutrients in their biomass become available to the following main crop (Rinnofner et al., 2008). Green fertilizers constitute both an important part of crop rotation and a valuable source of organic matter. Furthermore, they contribute to the increase of soil microbial activity, improve soil retention properties as well as increase mineral nutrient availability (Agustin et al., 1999; Sincik et al., 2008). In addition to agrotechnical aspects, the use of green fertilizers as preceding crops is ecologically beneficial (Krause et al., 2009; Nett et al., 2011). Potato demonstrates a strong response to cultivation after preceding crop plants (Munoz et al., 2005). Natural and organic fertilizers introduced into the soil result in a number of changes at a cultivation site, including those in nutrient supply (Tiwana and Narang, 1997; Fageria, 2007a). Stabilization of potato tuber yields requires regular control of macro- and micronutrient availability, as well as systematic organic matter incorporation into the soil (Van Delden, 2001; Zhang et al., 2007). Due to the short vegetation period, high yields and poorly developed root system, potatoes have high demand for immobile nutrients, i.e., phosphorus and potassium (Davenport et al., 2005; Fernandes et al., 2012, 2016a). The relationship between the plant root system length and phosphorus and potassium supply has been well documented in numerous publications (Chen and Gabelman, 2000; Hafsi et al., 2011; Fernandes et al., 2014). Potassium is the most accumulated nutrient by potato plantation. K^+ is an essential macronutrient for tuberization in the potato plant (Sharma and Arora, 1987). Chapman et al. (1992) demonstrated that there existed a close correlation between relative tuber yield and soil K, indicating that soil exchangeable K played an important role in potato tuberization. The main sources of K are mineral fertilizers, as well as manure – which is more and more often replaced with organic fertilizers and/or green fertilizers with low K concentration (Ceglarek and Buraczyńska, 2002). Every increase in the nitrogen dose has to be combined with an increase in the dose of potassium in a fertilizer. The mechanism of interaction between N and K has been well documented in subject literature (Marschner et al., 1996; Greenwood and Stone, 1998; Broadley et al., 2004). Uptake of nitrate ions, and then their transport in plants, in fact depend on K supply and requires constant delivery of this nutrient. However, it should also be noted that over 42% of soils in Poland exhibit low availability of available potassium (Lipiński, 2005).

The main nutritional factor that limits the growth of tuber biomass is the shortage of nitrogen, uptake of which depends on other nutrients. Nitrogen is critically important for potato canopy development, tuber initiation and yield quantity (Sattelmacher et al., 1990; Porter and Sisson, 1991; Belanger et al., 2001; Kołodziejczyk, 2014). Nitrogen levels have to be controlled both by regulating nutrient quantity in the soil and balancing other elements that condition nitrogen effectiveness in the plant (Grzebisz, 2011). Proper management of mineral nitrogen in the soil plays a key role in obtaining the optimal yield of good quality (Sincik et al., 2008). Both deficiency and excess of nitrogen can lead to yield reduction. The nitrogen level in potato tubers varies significantly depending on the duration of the vegetation period, and is reflected directly through the nitrate level (Rębarz et al., 2015).

The main reasons for the low use efficiency of nitrogen fertilizers by plants are the high losses via leaching, volatilization, inappropriate N balance, as well as neglecting micronutrients in fertilisation. Other important issue discussed in the recent years is a decline of micronutrient contents in the soil, which further proves the need for their additional application (Dimkpa and Bindraban, 2016). Increased interest in the effect of micronutrients on the yield size and crop quality is due to the fact that these very elements activate many enzymes and are responsible for the conversion of nitrogen absorbed by plants (Marschner, 2012). Yield enhancing activity of micronutrients is revealed under the conditions of their deficit as well as at higher production levels (Grzebisz, 2009). The likelihood of micronutrient deficiency in plants increases at sites with no manure treatment and those with light soils. Therefore, it is necessary to fertilize crops with micronutrients due to the real chance of their shortages (White and Broadley, 2009). According to existing subject literature, 40 t ha⁻¹ potatoes with tubers take up 100 g B, 60–70 g Cu, 450–500 g Zn, 700–750 g Mn and 2000 g Fe (Szewczuk, 2009).

The study was undertaken to test the research hypothesis that cultivation of stubble crops and foliar application of micronutrients had significant effects on the chemical composition of potato tubers. The field studies aimed to assess the effects of mineral fertilization on the concentration and accumulation of macronutrients (N, P, K, Mg and Ca) in potato tubers at the stage of technological maturity, as compared with manure fertilization and application of stubble intercrops (white mustard, pea, phacelia), as well as micronutrient foliar fertilization.

Materials and methods

In 2010–2012, the field experiment was conducted at the Wierzychucinek Research Station of the Bydgoszcz University of Technology and Life Sciences (53.2°N, 17.7°E), Poland. The subject of the study was early potatoes of the cultivar 'Bila'. A two-factor experiment was performed in a randomized complete block design with three replications. There were two study factors. The first factor was: fertilizer treatment, i.e., ($n=5$: NPK (control), NPK+farmyard manure; NPK+FYM, NPK+plowed white mustard intercrop (NPK+WM); NPK+plowed pea intercrop (NPK+Pe); NPK+plowed blue phacelia intercrop (NPK+PH)). The second factor was micronutrient foliar fertilization ($n=2$: no micronutrient treatment (M_0) and that with the application of micronutrients twice a vegetation season (M_1)). The plantation was not irrigated at the time of the study. Meteorological conditions varied over the study period (Table 1). The experiment was designed on lessive soil representing a "good for rye" soil complex (class

TABLE 1. Rainfall and temperature during the vegetation period of potatoes in 2010-2012.

Years	Months				
	IV	V	VI	VII	IV-VII
Rainfall (mm)					
1991-2015	29.0	61.2	58.8	87.8	236.8
2010	33.8	92.6	38.1	150.7	315.2
2011	13.5	38.4	100.8	132.5	285.2
2012	15.4	25.4	123.8	115.6	290.2
Temperature (°C)					
1991-2015	8.0	13.4	16.3	18.5	14.1
2010	7.8	11.5	16.7	16.6	13.1
2011	10.5	13.5	17.7	17.5	14.8
2012	8.4	14.8	17.8	18.8	14.9

TABLE 2. Basic physical and chemical properties of the soil used for the study.

Years	N tot (g kg ⁻¹)	P available (mg kg ⁻¹)	K available (mg kg ⁻¹)	Mg available (mg kg ⁻¹)	Sand (%)	Silt (%)	Clay (%)	C org. (g kg ⁻¹)	pH1M KCl
2010	0.65	47.13	220.66	40.61	57.3	38.4	4.3	4.42	5.7
2011	0.63	51.93	213.13	47.78	57.0	38.7	4.3	4.77	4.8
2012	0.69	51.13	240.34	41.17	57.3	38.4	4.3	4.33	5.4

IVa/IVb). The experiment was conducted on Albic Luvisol (IUSS, 2014), formed from glacial till, with Ap, Et, Bt, BC, C horizon sequence in soil profile, and sandy loam (18% of clay) texture in the ploughing horizon. Soil agrochemical properties prior to the experiment are given in Table 2.

The level of mineral fertilization remained the same throughout the study, and in the case of NPK treatment it was as follows: nitrogen 135 kg N ha⁻¹, phosphorus 32 kg P ha⁻¹, potassium 250 kg K ha⁻¹. The NPK doses were determined on the basis of potato nutritional needs, yield size and availability of soil nutrients. In the case of manure treatment, NPK rates applied were lower – reduced by the quantities introduced with manure, taking into account the percentage of the use in the first year, and amounted to: 90 kg N ha⁻¹, 25 kg P ha⁻¹ and 185 kg K ha⁻¹ in the study years. Manure was applied in the autumn, at a rate 30 t ha⁻¹. Phosphorus was introduced into the soil in the form of enriched superphosphate (17.5% P), and potassium – in the form of chloride potassium salt (49.8% K). Winter wheat was potato forecrop, whereas stubble intercrops (mustard, pea, phacelia) were sown after harvests in the first decade of August. In the second decade of October, manure was applied (incorporated by plowing to the depth of 18 cm). At the same time, intercrops were plowed into the ground. Then winter plowing was performed in order to mix manure and intercrops with the soil. NPK mineral fertilizers were applied in the spring, before potato tubers were planted. Micronutrients were applied as Symfonia MikroPlus fertilizer, sprayed in a chelated form (boron (B) 0.3%, copper (Cu) 0.12%, zinc (Zn) 0.30%, manganese (Mn) 0.9%, molybdenum (Mo) 0.05%). The micronutrient fertilizer was applied twice a vegetation season (3 dm³ ha⁻¹). The first foliar fertilization was conducted at the stage of early flowering (last ten days of June), and the second – two weeks later. Potatoes were planted in the second decade of April and harvested in the last decade of September. The size of each test plot was 45 m². Each plot consisted of 6 × 12 m-long rows, with the central two rows designed as

harvest rows. The distance between seed tubers was 25 cm and the distance between the rows was 0.625 m. Potato tubers were harvested by hand. Tuber yields were determined by weighing right after harvesting. For the assessments of nutrient concentration, 2 kg tubers were taken from each treatment.

The level of nitrogen in plant tissues was determined using the Kjeldahl method (Kjeltec 2200 FOSS auto-analyser). In order to determine the general level of P, K, Ca and Mg, ground tissue samples (1.5 g) were mineralised at 550°C for 6 hours. The ash was dissolved in 2 cm³ 0.15 M HNO₃. The level of phosphorus in the above solution was measured using the colorimetric method with vanadium-ammonium molybdate. The level of magnesium was measured using the Atomic Absorption Spectrometry method (SpectraAA-250Plus, Varian) of potassium and calcium flame emission spectroscopy. Chemical analyses of plant material were based on the SSSA methodological guide (Jones and Case, 1990). Uptake of nutrients was calculated multiplying the nutrient concentration by the amount of tuber dry mass of the tubers (DM values available from the authors).

The content and uptake of macronutrients in the years of the study were analysed using ANOVA in compliance with the applied additive linear model:

$$y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + e_{ijk}$$

where:

μ - average total;

α_i - effect of i -th micronutrient, $i=1$ without application $i=2$ with application;

β_j - effect of j -th fertilizer variants, $j=1, \dots, 5$;

e_{ijk} - sampling error.

The comparison of average nutrient content and absorption was conducted using Tukey's ($\alpha=0.05$); (Ott, 1984).

A simple correlation analysis and multiple regression analysis were used to estimate the causal relationship be-

tween the analysed parameters. The regression analysis was continued until all of the variables in the equation were significant for $p < 0.05$. Principal Component Analysis (PCA) was used to estimate causal relationships of data including nutrient uptake and content and potato tuber yields. The statistical analysis of the results was carried out using Statistica 13.1.

Results and discussion

Nutrient content in tubers

ANOVA results showed that macronutrient levels in potato tubers at the stage of technological maturity were significantly differentiated under the influence of the experimental factors, i.e., different variants of mineral fertilization in combination with manure or organic fertilizers applied before planting as well as foliar application of micronutrients (Table 3). No statistically significant differences were recorded for interactions between the experimental factors under the study. Irrespective of the study year, the highest content of nitrogen in tubers was obtained in the control treatment (mineral fertilization only), while the lowest N concentration was recorded in potato tubers cultivated after WM and PH intercrops. Lower nitrogen content in the tubers in WM and PH intercrop treatments may have resulted from the fact that the plant slows down the mineralisation of the organic substance and, as a result, the amount of nitrogen available for plants is/may be lower (Płaza, 2009). Two-time foliar application of microelement fertilizer also differentiated nitrogen contents, but statistically significant differences were found only in 2010 and 2012. Higher N content, regardless of the study year, was found in the variants without the use of micronutrients.

In the case of the concentration of phosphorus in tubers, differently than in relation to nitrogen, the largest nutrient (P) content was recorded in the site treated with FYM (Table 3). The fertilization treatments tested significantly reduced content of this nutrient, whose concentration decreased in the following order: NPK + FYM > NPK > NPK + Pe > NPK + WM > NPK + PH. In comparison to the normative values set by Walworth and Muniz (1993), the content of phosphorus in tubers was below the critical range (2–2.4 g kg⁻¹ d.m.). One of the reasons for the low content of phosphorus in tubers could be the level of this nutrient available in the soil, which in each year of the study was in the lower range of the average content.

In the study years, the experimental factor (mineral fertilization + intercrops) ambiguously differentiated the content of potassium in potato tubers (Table 3). The highest levels of K were recorded in manure treatment. The type of intercrop (NPK+Pe > NPK+WM > NPK+PH) had no effect on either potassium (except for 2011) or magnesium concentrations in tubers. The average K and Mg concentrations in potato tubers collected from plants cultivated after intercrops amounted to 23.6 g kg⁻¹ for potassium and 1.92 g kg⁻¹ for magnesium (Table 3). The levels of potassium and magnesium in the tubers examined were in the middle range of critical values, and, at the same time – higher than the values obtained by other authors (Wierzbicka and Trawczyński, 2011). Both the level of K available in the soil (reflecting the level of available K supply) and the stage of development of the root system are important factors determining the level of potassium in the plant. The tested potatoes were cultivated on the sites with high available potassium, between 213 and 240 mg K₂O per kg of the soil (Table 2). This shows that

K concentration depends a great deal on management practice and site conditions, including K status in the soil. In each study year, the highest Ca content in tubers was noted in the control variant, but the differences were not statistically significant when compared with other treatments. The content of calcium and magnesium was significantly differentiated by foliar application of micronutrients. Microelement fertilization caused a significant increase in calcium and magnesium content – by 11% and 4.6%, respectively, in comparison to M₀ objects. The content of all the analyzed nutrients was also diversified in the study years. These changes were due to variability of weather conditions. According to literature data, the influence of weather and environmental conditions is one of many factors differentiating the content and accumulation of nutrients in the plant, apart from mineral and organic fertilization, cultivation and fertilization systems and shifts (Marschner, 1986; Barłóg et al., 2013; Gaj et al., 2015). Changes in Ca and Mg concentrations in the tubers from intercrop treatments, may have resulted from the so-called dilution effect. It should be noted that tuber yields obtained from intercrop treatments were higher than those obtained in the control plots. The levels of Ca and Mg varied significantly as a result of foliar application of micronutrients. Microelement fertilization caused a significant increase in the levels of Ca and Mg – by 11% and 4.6%, respectively, when compared with M₀ treatment (no micronutrient fertiliser applied). Flis et al. (2012) state that macro-element concentrations in potato tubers are strongly correlated with tuber yields. Numerous studies prove that magnesium concentration is lower in the genotypes with higher yields. According to Kozera et al. (2006) fertilization with microelements, such as boron, copper and manganese, causes a significant reduction in the value of the sum of monovalent cations, narrowing the molar ratio of the sum of monovalent cations to the sum of divalent cations - (K + Na) : (Mg + Ca). The lower content of potassium increases the concentration of calcium and magnesium, and this in turn induces reduction of the molar ratio of the sum of monovalent cations to the sum of divalent cations.

The levels of all the analysed nutrients exhibited variation throughout the study, with the changes resulting from different weather conditions. During the vegetation seasons in the years 2011 and 2012, there was observed a significant water deficiency during the spring (April–May) (Table 1), resulting in lower levels of nitrogen, potassium and magnesium in potato tubers. Changing weather conditions at the site, like precipitation and temperature, may influence the yield through the modification of the growth rate and crop developmental stages. The year 2010 was the coldest year of the study, with the highest total precipitation. However, precipitation distribution differed significantly from the multi-annual average. The most favourable weather conditions for plant vegetation were observed in 2012. According to Żarski et al. (2014), mean annual precipitation on the investigated area is 374.6 mm, being one of the lowest values recorded in Poland. The multi-year average sums of precipitation and temperature (1981–2014) for Poland are 537 mm and 8.5°C, respectively (Żarski et al., 2010).

Analysis of correlation between tuber yields and the level of the analysed mineral nutrients, performed separately for each fertilization treatment, showed significant correlations in the case of nitrogen, potassium and magnesium. A significant negative correlation between the yield and the above nutrients was observed in each of the experimental variants under the study (Figure 1a). Moreover, other significant cor-

TABLE 3. Effects of fertilization system and application of micronutrients on macronutrient contents in potato tubers.

Year		Treatments	N	P	K	Ca	Mg
2010	M ₀	F (p-value)	13.03 _(p<0.05)	21.74 _(p<0.05)	3.01 _(p<0.05)	2.08 _(p=0.16)	2.89 _(p<0.05)
		Control (NPK)	17.66 ^a	2.37 ^b	23.18 ^a	1.02 ^a	1.95 ^b
		NPK+FYM	17.02 ^a	2.57 ^a	24.42 ^a	0.95 ^a	2.12 ^a
		NPK+WM	15.76 ^b	2.12 ^c	22.86 ^a	0.89 ^a	2.04 ^{ab}
		NPK+Pe	16.68 ^{ab}	2.24 ^{bc}	23.98 ^a	0.98 ^a	2.05 ^{ab}
		NPK+PH	15.82 ^b	2.15 ^c	22.83 ^a	0.89 ^a	2.03 ^{ab}
	M ₁	F (p-value)	6.86 _(p<0.05)	3.77 _(p<0.05)	5.12 _(p<0.05)	2.86 _(p=0.08)	3.6 _(p<0.05)
		Control (NPK)	17.21 ^a	2.06 ^b	23.34 ^{ab}	1.18 ^a	2.03 ^b
		NPK+FYM	16.35 ^{ab}	2.26 ^a	24.65 ^a	1.12 ^a	2.18 ^a
		NPK+WM	15.64 ^b	1.86 ^c	22.22 ^b	1.04 ^a	2.09 ^{ab}
		NPK+Pe	16.57 ^{ab}	1.97 ^{bc}	24.15 ^{ab}	1.15 ^a	2.10 ^{ab}
		NPK+PH**	15.50 ^b	1.85 ^c	22.29 ^b	1.07 ^a	2.11 ^{ab}
		F (p-value)	4.60 _(p<0.05)	169.56 _(p<0.05)	0.12 _(p=0.2)	51.22 _(p<0.05)	9.16 _(p<0.05)
		M ₀	16.59 ^A	2.30 ^A	23.46 ^A	0.95 ^B	2.04 ^B
		M ₁	16.25 ^B	2.00 ^B	23.33 ^A	1.11 ^A	2.01 ^A
			N	P	K	Ca	Mg
2011	M ₀	F (p-value)	5.49 _(p<0.05)	40.49 _(p<0.05)	7.11 _(p<0.05)	2.22 _(p=0.14)	18.35 _(p<0.05)
		Control (NPK)	15.79 ^a	2.20 ^b	21.93 ^a	1.05 ^a	1.63 ^c
		NPK+FYM	15.12 ^{ab}	2.38 ^a	22.56 ^a	0.98 ^a	1.80 ^a
		NPK+WM	14.46 ^b	2.04 ^c	21.48 ^{ab}	0.92 ^a	1.74 ^{ab}
		NPK+Pe	14.78 ^{ab}	2.19 ^b	19.68 ^b	0.97 ^a	1.73 ^b
		NPK+PH	14.53 ^b	1.97 ^c	21.56 ^a	0.94 ^a	1.74 ^{ab}
	M ₁	F (p-value)	8.63 _(p<0.05)	23.11 _(p<0.05)	1.04 _(p=0.43)	3.46 _(p<0.05)	8.33 _(p<0.05)
		Control (NPK)	15.06 ^a	2.02 ^b	21.64 ^a	1.17 ^a	1.74 ^b
		NPK+FYM	14.75 ^{ab}	2.14 ^a	21.96 ^a	1.10 ^{ab}	1.91 ^a
		NPK+WM	14.24 ^b	1.91 ^{cd}	21.15 ^a	1.05 ^{ab}	1.77 ^b
		NPK+Pe	14.59 ^b	1.99 ^{bc}	20.10 ^a	1.08 ^{ab}	1.76 ^b
		NPK+PH	14.18 ^b	1.89 ^d	21.15 ^a	1.02 ^b	1.78 ^b
		F (p-value)	3.79 _(p=0.07)	131.40 _(p<0.05)	0.46 _(p=0.50)	31.41 _(p<0.05)	26.24 _(p<0.05)
		M ₀	14.93 ^A	2.16 ^A	21.44 ^A	0.95 ^B	1.73 ^B
		M ₁	14.67 ^A	1.99 ^B	21.20 ^A	1.08 ^A	1.79 ^A
			N	P	K	Ca	Mg
2012	M ₀	F (p-value)	8.85 _(p<0.05)	33.18 _(p<0.05)	6.37 _(p<0.05)	2.11 _(p=0.15)	4.37 _(p<0.05)
		Control (NPK)	16.19 ^a	2.29 ^b	22.41 ^{ab}	1.09 ^a	1.80 ^b
		NPK+FYM	15.77 ^{ab}	2.47 ^a	23.48 ^a	1.05 ^a	1.99 ^a
		NPK+WM	14.70 ^c	2.09 ^c	21.81 ^b	0.96 ^a	1.86 ^{ab}
		NPK+Pe	15.34 ^{abc}	2.19 ^{bc}	21.81 ^b	1.00 ^a	1.89 ^{ab}
		NPK+PH	14.93 ^{bc}	2.11 ^c	21.88 ^b	0.98 ^a	1.87 ^{ab}
	M ₁	F (p-value)	14.65 _(p<0.05)	16.18 _(p<0.05)	2.38 _(p=0.12)	4.67 _(p<0.05)	13.85 _(p<0.05)
		Control (NPK)	15.87 ^a	2.10 ^{ab}	22.05 ^a	1.18 ^a	1.89 ^c
		NPK+FYM	15.19 ^{ab}	2.22 ^a	22.97 ^a	1.11 ^{ab}	2.11 ^a
		NPK+WM	14.28 ^c	1.89 ^c	21.54 ^a	1.04 ^b	2.01 ^b
		NPK+Pe	14.90 ^{bc}	1.98 ^{bc}	21.54 ^a	1.07 ^{ab}	2.05 ^{ab}
		NPK+PH	14.32 ^c	1.87 ^c	21.54 ^a	1.02 ^b	1.99 ^b
		F (p-value)	15.81 _(p<0.05)	117.96 _(p<0.05)	2.47 _(p=13)	10.31 _(p<0.05)	50.56 _(p<0.05)
		M ₀	15.39 ^A	2.23 ^A	21.93 ^A	1.06 ^B	1.88 ^B
		M ₁	14.91 ^B	2.01 ^B	22.28 ^A	1.08 ^A	2.01 ^A
			N	P	K	Ca	Mg

* Means with the same letter are not significantly different; $\alpha=0.05$ (Tukey's test); M₀ without the application of micronutrients; M₁ - with double application of micronutrients; NPK (control).

** NPK+cattle manure: NPK+ploughed white mustard intercrop (NPK+WM); NPK++ploughed pea intercrop (NPK+Pe); NPK+ploughed *Phacelia tanacetifolia* intercrop (NPK+PH).

TABLE 4. Effects of cultivation system and application of micronutrients on macronutrient accumulation in potato tubers.

Year		Treatments	N	P	K	Ca	Mg
2010	M ₀	F _(p-value)	10.12 _(p<0.05)	10.61 _(p<0.05)	9.20 _(p<0.05)	1.51 _(p=0.22)	41.44 _(p<0.05)
		Control (NPK)	60.73 ^{c*}	8.18 ^b	79.86 ^b	3.50 ^a	6.72 ^b
		NPK+FYM	67.04 ^a	10.20 ^a	79.00 ^a	3.76 ^a	8.43 ^a
		NPK+WM	61.38 ^{bc}	8.25 ^b	88.99 ^{ab}	3.48 ^a	7.96 ^a
		NPK+Pe	64.99 ^{ab}	8.74 ^b	83.47 ^a	3.83 ^a	7.80 ^a
		NPK+PH**	61.93 ^{bc}	8.41 ^b	89.37 ^{ab}	3.47 ^a	7.96 ^a
	M ₁	F _(p-value)	5.30 _(p<0.05)	20.68 _(p<0.05)	12.40 _(p<0.05)	2.05 _(p=0.08)	39.09 _(p<0.05)
		Control (NPK)	68.07 ^b	2.15 ^b	92.29 ^c	4.68 ^a	8.03 ^c
		NPK+FYM	74.26 ^a	10.25 ^a	111.92 ^a	5.08 ^a	9.93 ^a
		NPK+WM	68.70 ^{ab}	8.16 ^b	97.64 ^{bc}	4.57 ^a	9.17 ^b
		NPK+Pe	72.05 ^{ab}	8.59 ^b	104.97 ^{ab}	5.02 ^a	9.15 ^b
		NPK+PH	67.98 ^b	8.12 ^b	97.81 ^{bc}	4.69 ^a	9.24 ^b
		F _(p-value)	101.46 _(p<0.05)	0.49 _(p<0.5)	20.87 _(p<0.05)	3.48 _(p<0.05)	74.73 _(p<0.05)
		M ₀	63.34 ^B	8.75 ^A	89.74 ^B	3.61 ^B	7.81 ^B
		M ₁	70.21 ^A	8.65 ^A	100.93 ^A	4.81 ^A	9.10 ^A
2011	M ₀	F _(p-value)	21.23 _(p<0.05)	27.74 _(p<0.05)	22.52 _(p<0.05)	6.41 _(p<0.05)	20.42 _(p<0.05)
		Control (NPK)	133.25 ^b	18.61 ^{bc}	184.90 ^b	8.83 ^{ab}	13.76 ^c
		NPK+FYM	150.23 ^a	23.64 ^a	224.36 ^a	9.77 ^a	17.93 ^a
		NPK+WM	128.48 ^b	18.11 ^{bc}	190.99 ^b	8.14 ^b	15.51 ^b
		NPK+Pe	135.75 ^b	20.11 ^b	180.73 ^b	8.93 ^{ab}	15.86 ^b
		NPK+PH	128.24 ^b	17.41 ^c	190.27 ^b	8.29 ^b	15.36 ^b
	M ₁	F _(p-value)	14.06 _(p<0.05)	44.91 _(p<0.05)	9.49 _(p<0.05)	6.55 _(p<0.05)	26.08 _(p<0.05)
		Control (NPK)	136.53 ^b	17.65 ^{bc}	186.09 ^b	10.27 ^{ab}	15.22 ^b
		NPK+FYM	155.44 ^a	22.59 ^a	231.40 ^a	11.55 ^a	20.14 ^a
		NPK+WM	131.67 ^b	17.63 ^{bc}	159.61 ^b	9.74 ^b	16.40 ^b
		NPK+Pe	139.56 ^b	19.04 ^b	193.28 ^b	10.30 ^{ab}	16.81 ^b
		NPK+PH	131.25 ^b	17.37 ^c	195.60 ^b	9.36 ^b	16.48 ^b
		F _(p-value)	6.37 _(p<0.05)	7.97 _(p<0.05)	4.77 _(p<0.05)	68.33 _(p<0.05)	36.45 _(p<0.05)
		M ₀	135.19 ^B	19.57 ^A	194.25 ^B	8.78 ^B	15.68 ^B
		M ₁	138.89 ^A	18.86 ^B	200.80 ^A	10.26 ^A	17.01 ^A
2012	M ₀	F _(p-value)	29.86 _(p<0.05)	100.17 _(p<0.05)	90.23 _(p<0.05)	6.23 _(p<0.05)	50.35 _(p<0.05)
		Control (NPK)	110.02 ^c	15.54 ^c	152.29 ^d	7.41 ^b	12.26 ^{bc}
		NPK+FYM	138.59 ^a	21.74 ^a	206.31 ^a	9.23 ^a	17.49 ^a
		NPK+WM	114.04 ^c	16.18 ^c	169.14 ^c	7.45 ^b	14.45 ^c
		NPK+Pe	127.28 ^b	18.19 ^b	180.89 ^b	8.29 ^{ab}	15.71 ^b
		NPK+PH	117.14 ^c	16.59 ^c	171.61 ^{bc}	7.66 ^b	14.64 ^{bc}
	M ₁	F _(p-value)	60.63 _(p<0.05)	47.15 _(p<0.05)	34.27 _(p<0.05)	9.96 _(p<0.05)	120.79 _(p<0.05)
		Control (NPK)	118.48 ^c	15.66 ^c	164.63 ^c	8.81 ^b	14.09 ^d
		NPK+FYM	147.46 ^a	21.53 ^a	223.12 ^a	10.75 ^a	20.49 ^a
		NPK+WM	123.51 ^c	16.37 ^c	186.22 ^b	8.99 ^b	17.35 ^c
		NPK+Pe	135.47 ^b	18.0 ^b	195.84 ^b	9.76 ^{ab}	18.64 ^b
		NPK+PH	121.82 ^c	15.93 ^c	183.22 ^b	6.65 ^b	16.93 ^c
		F _(p-value)	46.06 _(p<0.05)	0.59 _(p<0.06)	59.75 _(p<0.05)	55.99 _(p<0.05)	282.96 _(p<0.05)
		M ₀	121.42 ^B	17.65 ^A	176.05 ^B	8.01 ^B	14.91 ^B
		M ₁	129.35 ^A	17.50 ^A	190.60 ^A	9.39 ^A	17.50 ^A

* See Table 3.

FIGURE 1. Two-dimensional projection of potato tuber dry mass and yields as well as nutrient and starch contents; a. Control; b. NPK + FYM.

relations between the levels of nutrients in the tubers were observed: nitrogen concentration correlated positively with potassium and magnesium levels, and – in the case of the site where manure was applied – a significant correlation between nitrogen and phosphorus (Figure 1b). Nutrients seldom act separately. Throughout plant growth, the concentrations of nutrients change relative to one another in the soil and within the plant. Element concurrence can be of synergic or antagonistic character. Numerous researches indicated that firstly the interaction between nitrogen and other elements influenced the yield obtained and nitrogen utilization (Fixen et al., 2005; Roberts, 2008).

The content and amount of potassium in potatoes are determined by nitrate uptake from the soil. Phosphorus, with the participation of magnesium, affects the correct course of basic plant processes responsible for metabolic energy generation needed for effective binding of carbon dioxide as well as nutrient uptake (Marschner, 1986). The absorption of P depends on N level of in the plant. Nitrogen deficiency increases root/shoot ratio (Ericsson, 1995; Poorter and Nagel, 2000), which can increase P uptake relative to plant demands (Tinker and Nye, 2000). The interaction between nitrogen and phosphorus has been widely discussed in subject literature (Tinker, 2003; Sadras, 2006; Zhang et al., 2007). In addition, both nitrogen and phosphorus take part in the processes of photosynthesis and protein synthesis.

Nutrient accumulation

The experimental factors caused significant differentiation between uptake levels as regards each nutrient under the study (Table 4). In every year of the study, the highest accumulation of all the analysed nutrients was recorded in the treatment where manure and micronutrients were applied (with the exception of phosphorus – treatments M₁, the years 2010 and 2012). This relationship results from improved supply of manure nutrients in the plant and their gradual release during the vegetation period. In each year of the study, the largest accumulation of all the analyzed nutrients was observed in the experimental variant with manure treatment and micronutrient foliar application. Only in the case of P, regardless of the study year, higher accumulation values were recorded in manure treatment with no micronutrient application.

The total N uptake ranged from 60 to 155.4 kg N ha⁻¹ and varied significantly in response to the experimental factors and the study years (Table 4). Among the intercrops under the study, the highest accumulation of nitrogen was recorded in potato tubers cultivated after pea intercrop. When com-

pared to the control, the average differences in N uptake ranged between 4 to 17 kg N ha⁻¹ (Table 4). The results obtained by Rinnofner et al. (2008) also showed an increase in N uptake by potatoes cultivated after intercrop plants, with the difference ranging between 12 and 31 kg N ha⁻¹. In the present study, irrespective of the observation year, higher quantities of nitrogen were accumulated by the plants treated with micronutrient fertilizer. The greatest difference (12%), between micronutrient fertilized and micronutrient not-fertilized plants was recorded in 2010, whereas in the following years the differences were 3% and 6%. The results demonstrate the importance of micronutrients in nitrogen management. Micronutrients activate a series of physiological processes, resulting in the increase of nitrogen effectiveness in a fertilizer (Datnoff et al., 2007; Marschner, 2012).

In the case of phosphorus accumulation (in 2010 and 2012), the value of uptake decreased in the following order: NPK+FYM>NPK+Pe>NPK+WM>NPK+PH>control (Table 4). In 2011, the accumulation of P in potato tubers looked somewhat different: NPK+FYM>NPK+Pe>control>NPK+WM>NPK+PH (Table 4). Manure treatment differed significantly from the rest of the treatments examined. Application of micronutrient fertilizer did not result in increased nutrient uptake in comparison with no-micronutrient fertilization. A statistically significant difference between the experimental variants with and without micronutrients was observed only in 2011, and amounted to 3.62%. In 2010 and 2012, a decrease in P accumulation under the influence of foliar application of micronutrients was observed: by 1.14% in 2010

FIGURE 2. Effects of cultivation systems on nutrient uptake (mean from years 2010–2012).

FIGURE 3. Two-dimensional projection of nutrient uptake, yield, dry mass and starch in potato tubers; a. control; b. NPK+PH.

and 0.8% in 2012. One of the reasons of lower accumulation of P in potato tubers due to foliar application of micronutrient fertilizer may be the antagonism between phosphorus and zinc introduced via the foliar fertilizer (Fernandes and Soratto, 2016b). Large amounts of zinc reduce P uptake (Mousavi, 2011). According to Kizilgoz and Sakin (2010), P/Zn relations in the plant allow to assess P and Zn status in the plant. The effect of zinc has to be considered in view of both the soil and the plant. An excess of phosphorus in the soil leads Zn regress into the form of an inactive orthophosphoric precipitate, followed by the blockage of zinc cation uptake by calcium cations, which are absorbed along with orthophosphoric anions. The antagonistic effect of phosphorus in the plant results from binding zinc by orthophosphoric residues in the root apoplast and cell cytoplasm (Cakmak and Marschner, 1987). Other studies (Khan et al., 1986; Ishaq et al., 2001) showed that P absorption depends significantly on the method of soil cultivation, which is directly related to the development of the root system and, as a consequence, has an impact on the uptake of water and mineral nutrients. Alvarez-Sanches et al. (1999) showed that only 4–6.5% of P applied in fertilizer was absorbed by potato plants.

Among the elements under the study, K was the dominant nutrient in the accumulation structure (Table 4). Notwithstanding the study year, a significant increase in K uptake was observed in manure treatment, when compared with the control. FYP treatment differed significantly from all other treatments in the years 2011 and 2012. The use of manure results in incorporation of a number of macro- and micronutrients, and improves the effectiveness of the process of nutrient uptake from soil resources. When compared with the control (no micronutrient fertilizer), a significant increase in K absorption was observed in each year of the study as a result of the application of micronutrient fertilizers.

A significant increase in nutrient uptake as a result of micronutrient fertilizer application was also observed in the case of calcium and magnesium accumulation. When compared with the control (no-micronutrient treatment), the differences were: 19.85% for calcium and 13.6% for magnesium. The total accumulation of nutrients also depended on the study year. The lowest accumulation of all the nutrients analyzed was observed in 2010, resulting directly from the lower tuber yields as compared to other study years (Murawska et al., 2015).

A synthesis of the results of the 3-year-long study, concerning all the analyzed nutrients, showed that the effects of

intercrops on macronutrient accumulation decreased in the following order: pea > mustard > phacelia, with the exception of nitrogen, for which the order was: pea > phacelia > mustard (Figure 2). The comparison of nutrient accumulation in the tubers dependent on the intercrops showed significant differences in the case of nitrogen and phosphorus in pea intercrop treatment, and this variant differed significantly from the remaining intercrops tested (mustard and phacelia). Literature data show that both potato yield response to green fertilizers (Sincik et al., 2008) and nutrient accumulation in plants cultivated after intercrops, are assessed on the basis of not only yield size and quality, but also the structure-forming effect of intercrop plants and water management. The increase in phosphorus uptake under the influence of the used green fertilizers resulted from an increase in the solubility of organic phosphorus compounds and inorganic phosphates in the soil under the influence of root secretions of catch crop plants in the contact zone of their roots with the solid phase of the soil. (Sharply and Smith, 1989). Moreover, green fertilizers accumulate, in general, higher quantities of phosphorus and, as a result, the quantity of P from decomposition of green fertilizers is higher. In the present study, the total uptake of phosphorus ranged between 8 and 20 kg P ha⁻¹ and was lower than the values (25–35 kg ha⁻¹) reported by Davenport et al. (2005). The variation in the quantity of phosphorus uptake depends not only on different plant nutritional needs, but also on the development of the root system. The structure of root systems plays a significant role in P absorption, and this is related to low mobility of this nutrient in the soil (Forde and Lorenzo, 2001).

The effects of intercrops on nitrogen, phosphorus and potassium uptakes were similar, and in most cases, there were no significant differences between the treatments. The correlation analysis as regards tuber yields, dry mass and starch as well as the total accumulation of nutrients, showed that regardless of the experimental variant analyzed, there was a highly significant correlation between yield/starch content and uptake of all the macronutrients under the study. A graphic interpretation of the correlations between tuber yield/starch content and nutrient accumulation in the tubers was determined by PCA (Figure 3a, control). Depending on the intercrop type, different correlations were found between the amounts of potato tuber dry mass and nutrient accumulation. Regardless of the treatment, a positive correlation between tuber dry mass and magnesium accumulation was found. In the case of other nutrients studied, correlations depended on

the type of intercrop and were as follows: pea – phosphorus and magnesium, white mustard – potassium and magnesium, phacelia – phosphorus, potassium and magnesium (Figure 3b, exemplified with phacelia). The role of magnesium, phosphorus, potassium and intercrops in the production of potato dry mass was also highlighted by other authors (Fernandes et al., 2015; Sincik et al., 2008).

Conclusions

1. The experimental factors caused significant differentiation of the levels of the studied macronutrients in potato tubers. The highest concentrations of N and Ca were observed in the control, whereas the highest P, K and Mg concentrations – in tubers of potato plants cultivated in manure treated soil.
2. The influence of stubble crops on the level of the studied nutrients in tubers varied depending on the nutrient and was as follows:
 - Excluding potassium, the highest levels of the analysed macronutrients were observed in pea intercrop treatment;
 - Phacelia and mustard intercrops were the strongest drivers of the reduction of nitrogen and phosphorus levels in potato tubers.
3. Notwithstanding the experimental treatments, a significant negative correlation between potato tuber yield and the levels of all of the analyzed nutrients was found.
4. On average, the highest quantity of macronutrients under the study, independently of micronutrient application and the study year, was absorbed by potato tubers collected from manure-treated plots. Nitrogen and phosphorus uptake was differentiated by the type of intercrop in the following order: pea > mustard > phacelia. Potassium, calcium and magnesium uptake was analogous in intercrop treated plots.
5. As compared to the control (no micronutrient application), foliar micronutrient fertilisation resulted in the increase in nitrogen, potassium, calcium and magnesium uptake. However, statistically significant differences were found only in the case of calcium and magnesium.
6. Cultivation of stubble crops (phacelia, mustard, pea) together with micronutrient application and mineral fertilization significantly modified the chemical composition of potato tubers, which in consequence, influenced their quality characteristics. Accordingly, intercropping may be an alternative to manure in potato fertilization as it does not require large expenditure, and constitutes the source of macronutrients and organic matter, as well as improves soil structure and prevents its degradation.

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