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ORIGINAL PAPER

EFFECT OF COMPANION CROPS AND CROP ROTATION SYSTEMS ON SOME CHEMICAL PROPERTIES OF SOIL*

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Abstract

The aim of the experiment, conducted in 2005-2011, was to make an assessment of the influence of spring spring barley sowing technology (pure and with companion crops) in crop rotation sequences with 25, 50 and 75% shares of spring spring barley on chemical changes in the 0-20 cm soil horizon. In 2011, spring spring barley (pure sowing) on a stand where spring barley preceded spring barley in a crop rotation system with a 50% spring barley share was found to cause a decline in soil pH and a rise in the soil content of organic carbon (C org.) in comparison with the treatments where companion crops were undersown. Spring barley with the companion crop of Italian ryegrass on a spring barley after spring barley stand raised the pool of C org. in soil relative to the period before the experiment, but the opposite effect was observed when spring barley was undersown with red clover on a stand after potato. In the pure stand, after seven years of the experiment, the highest increase in the soil phosphorus (P) content was noted under the spring barley field following spring wheat, whereas on the plots with the Italian ryegrass companion crop in a sequence of spring barley after spring barley repeated twice the soil was richer in P than prior to the experiment. Once the experiment was terminated in 2011, more potassium (K) was determined in soil under pure spring barley than under spring barley with companion crops. Spring barley with Italian ryegress as a companion crop raised the content of K in soil, but a reverse situation was observed on plots with red clover undersown on a stand of spring barley after potato in comparison with the crop rotation sequences of spring barley after spring wheat and after spring barley. In the case of the soli pH and phosphorus, a positive correlation was noted in the sequence of spring barley undersown with red clover on a stand after spring barley in the crop rotation system with a 75% of spring barley.

Keywords: quality of soil, spring spring barley, crop rotation, preceding crop, companion crops.

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INTRODUCTION

Sowing as a basic element of agrotechnics determines soil conditions at the field scale, crop architecture, plant growth, crop size and quality (Jaskulska et al. 2018, Jaskulska et al. 2019). Intensification of agriculture and a rapid rate of mechanisation of all field works have led to substantial simplifications in crop rotation management. Farmers have reduced or even eliminated labour-consuming crops, mostly sowing cereals instead (Smagacz, Kuś 2010). The growing share of cereals in the structure of sown crops as well as the practice of growing cereal after cereal tend to cause negative changes in the soil environment. Diversity and activity of soil organisms diminish, while concentrations of bioactive compounds that interfer with the growth and development of crops increase. A loss of organic matter and nutrients is seen, which consequently affects the yields of crops (Souchere et al. 2003, Fanglong et al. 2007).

A factor which can considerably alleviate the negative consequences of erroneous crop sequences is the cultivation of catch crops and companion crops intended for annual use (Andrzejewska 1999, Askegaard, Eriksen 2008). Cultivation of companion crops in modern field production is one of the ways to improve the biodiversity of agricultural ecosystems. Their introduction into crop rotation systems improves the sanitary condition of soil and protects soil from aquatic and eolic erosion (Kuś, Jończyk 2000). Kaspar et al. (2001) maintain that the anti-erosive effect of companion crops depends on the biology of cover plants and habitat conditions, as well as the intensity and distribution of rainfalls during the plant growing season. Companion crops have a positive influence on the physical, chemical and biological properties of soil (Sharratt 2002, Thorup-Kristensen et al. 2003). They raise the content of macronutrients in soil, improve soil structure, increase the soil pH and limit the leaching of nutrients to deeper soil horizons (Eriksen, Thorup-Kristensen 2002, Askegaard, Eriksen 2008). Moreover, they provide substantial amounts of biomass and post-harvest residues, thus enriching soil with organic carbon (Børresen 1995, Thomson, Christensen 2004, Wanic et al. 2013). In recent years, there have been many articles dealing with the role of catch crops in crop rotation systems with excessive contribution of cereals (Børresen 1995, Askegaard, Eriksen 2008, Wanic et al. 2013). Little information can be found, unfortunately, about companion crops, which can induce greater positive changes in the soil chemical properties than stubble or winter catch crops.

The objective of this study has been to make an assessment of the impact of companion crops grown with spring spring barley in crop rotation systems with 25, 50 and 75% shares of spring barley on selected chemical characteristics of soil.

MATERIALS AND METHODS

The research data were acquired during a controlled, two-factorial field experiment, established in Bałcyny (53°36′ N, 19°51′ E), an experimental station owned by the University of Warmia and Mazury in Olsztyn, and carried out from 2005 until 2011 on the same location. The experiment, consisting of 4 replications, comprised 128 plots, each with an area for harvest equal 18 m^2 . Until the year 2004, the huskless spring barley cultivar Rodion had been grown there, and the fields cropped with this cereal in pure stands had been protected by chemical methods.

The experiment was set up on a Haplic Luvisol (Aric, Ochric) soil developed from loamy sand (LS) and underlain by sandy loam (SL).

The standard sowing density for cv. Rastik in pure stand and undersown was 500 sprouting kernels per 1 m^2. In the plots with companion crops, 15 kg ha^{-1} of red clover or 24 kg ha^{-1} of Italian ryegrass were sown with spring barley.

Doses of mineral fertilisers were not differentiated among the spring barley sowing technologies or crop rotation systems. They were (kg ha^{-1}): N – 60.0, P – 34.9 and K – 66.4. Once during a four-year crop rotation sequence, manure in a dose of 25 t ha^{-1} was applied under potato.

The experimental factors:

1. Spring barley sowing methods:
   - pure sowing (with chemical protection),
   - sowing with companion crops (without chemical protection).
2. Position of spring barley in 4 crop rotation systems, including different shares of spring barley and cereals:

Crop rotations with pure spring barley and the following selection and sequence of crops

Crop rotations:

A: potato – spring barley* – seed pea – spring wheat (25% of spring barley share, 50% of cereals – the control treatment);

B: potato – spring barley** – spring wheat – spring barley* (50% of spring barley, 75% of cereals);

C: potato – spring wheat – spring barley** – spring barley* (50% of spring barley, 75% of cereals);

D: potato – spring barley* – spring barley** – spring barley* (75% of spring barley, 75% of cereals).

Where:

* in pure stand or with a companion crop of Italian ryegrass,

** in pure stand or with a companion crop of red clover.

Soil tillage in all plots was performed in a ploughing system, and the biomass of both companion crops was ploughed into the soil in the autumn to a depth of around 25 cm.

On average for the 7-year study period, yields of dry matter of both companion crops were *ca* 6.15 t ha^{-1}. The highest biomass of undersown Italian ryegrass was noted on a stand of spring barley after spring barley (crop rotation C), while the lowest one (6.16 and 6.22 t ha^{-1}) was recorded after potato and twice repeated cultivation of spring barley after spring barley (four-field crop rotation D). Red clover as a companion crop yielded significantly worse on a stand of spring barley after spring barley (four-field crop rotation D), while producing the best yield (6.38 t ha^{-1}) on a spring barley stand after potato (crop rotation B). In the years 2005-2011, on average per year, the amounts of dry matter added to soil were from 5.54 to 6.38 t ha^{-1} of red clover companion crop d.m. and from 6.16 to 6.46 t ha^{-1} of Italian ryegrass companion crop d.m. (Table 1).

Table 1

Dry matter yields of undersown crops (t ha^{-1}), means from the years 2005-2011

Undersown crop	Crop rotation with spring spring barley (%), preceding crop								Average
	A - 25	B - 50		C - 50		D - 75			
	potato A	potato B1	spring wheat B2	spring wheat C1	spring barley C2	potato D1	spring barley D2	spring barley D3	
Italian ryegrass	6.34*ab*	x	6.27*ab*	x	6.46*a*	6.16*b*	x	6.22*c*	6.29
Red clover	x	6.38*ab*	x	6.07*bc*	x	x	5.54*d*	x	6.00

a, *b*…*d* – homogenus group according to the Tukey test at $p < 0.05$

Chemical analyses of soil were made in the spring 2005 (before the experiment) and after the experiment was completed in 2011. Samples for analyses were collected from each plot with a soil sampler, from the 0-20 cm soil layer at 4 fixed sites. The following determinations were made: soil pH (1 mol KCl), content of organic carbon and assimilable forms of phosphorus, potassium and magnesium. The soil pH was determined by potentiometry, organic carbon by calorimetry via oxidation with a solution of $K_2Cr_2O_7$ + + H_2SO_4 and measuring the absorption on a spectrophotometer. The available forms of phosphorus were determined with the spectrophotometric method, potassium – by flame photometry, and magnesium – by flame atomic absorption spectrometry. All analyses were made in an accredited laboratory of the Agricultural Chemical Station in Olsztyn.

The data achieved from the above analyses were processed statistically. Significance of differences between the means from the year 2005 versus 2011 were assessed with the t-Student test for dependent samples. Analysis of the significance of differences between the means from the year 2011 was carried out with the Tukey's test at $p < 0.05$. In addition, the Pearson's correlation analysis was made between the yield of dry matter of both companion crops and the soil pH as well as the soil content of the determined macronutrients. All calculations were supported by Statistica® 13 software (TIBCO Software Inc. 2017).

RESULTS

During the seven years of the experiment (pure stand), a spring barley stand in a crop rotation sequence modified the soil pH only under spring barley grown after spring barley in a four-field crop rotation where spring barley made up 50% of the crops (Table 2). Relative to the year 2005, a significantly lower soil pH was noted (less by 0.21 units, i.e. by 3.8%). No significant differences in this parameter were determined between the two companion crops.

In 2011, a significantly higher (by 0.28 unit on average) soil acidity was noted on plots with companion crops compared with pure stands. In pure stands (four-field treatment D), in the plot of spring barley after spring barley a tendency towards decreasing soil pH was observed (pH 5.30) alongside an increase in the same parameter (pH 5.56) in the spring barley after potato sequence. The companion crop of Italian ryegrass decreased the soil pH in a stand with the twice repeated sequence of spring barley after spring barley in the four-field crop rotation system with a 75% share of spring barley. A similar situation was observed on the plots with red clover as a companion crop when spring barley followed potato or spring wheat in crop rotations B and C. For both companion crops, the differences noted were not supported by the statistical analysis and appeared more like a trend.

After the experiment was terminated (pure sowing), relative to the situation in 2005, considerably more organic carbon (by 0.45 g kg^{-1}) was determined in the stand of spring barley grown after spring barley (four-field treatments C and D), with the spring barley after spring barley sequence in the crop rotation with a 50% share of spring barley highly significantly varying the analysed parameter (Table 3). More organic C in soil was also found when spring barley was grown after spring wheat (four-field crop rotations B and C), although the differences observed were more of a trend. The other stands depleted the pool of C in soil in comparison with the situation noted in 2005 (the year the experiment was started). The highest decrease (by 1.18 g kg^{-1}) appeared when spring barley followed potato in four-field crop rotation B, but the differences were not confirmed statistically, either.

In 2011, significantly more organic carbon in soil (by 0.42 g kg^{-1}) was determined in pure stands than in plots with the companion crops. The tested spring spring barley stands (pure sowing) considerably dimin-

Table 2

Soil pH in 1 M KCl before the establishment (2005) and after the completion of the field experiment (2011)

Years Stand type	Crop rotation with spring spring barley (%), preceding crop								Aver- age
	A - 25	B - 50		C - 50		D - 75			
	potato A	potato B1	spring wheat B2	spring wheat C1	spring barley C2	potato D1	spring barley D2	spring barley D3	
Pure stand									
2005	5.46	5.46	5.45	5.47	5.56	5.49	5.48	5.46	x
2011	5.38	5.35	5.39	5.39	5.35	5.56	5.30	5.35	x
t-Student	ns	ns	ns	ns	*	ns	ns	ns	x
With Italian ryegrass companion crop									
2005	5.63	x	5.67	x	5.66	5.77	x	5.60	x
2011	5.66	x	5.60	x	5.65	5.65	x	5.53	x
t-Student	ns	x	ns	x	ns	ns	x	ns	
With red clover companion crop									
2005	x	5.62	x	5.72	x	x	5.87	x	*x*
2011	x	5.64	x	5.64	x	x	5.83	x	*x*
t-Student	x	ns	x	ns	x	x	ns	x	x
2011									
Pure stand	5.38*a*	5.35*a*	5.39*a*	5.39*a*	5.35*a*	5.56*a*	5.30*a*	5.35*a*	5.38*B*
With Italian ryegrass companion crop	5.66*a*	x	5.60*a*	x	5.65*a*	5.65*a*	x	5.53*a*	5.62*A*
With red clover companion crop	x	5.64*a*	x	5.64*a*	x	x	5.83*a*	x	5.70*A*
Average	5.52 ns	5.50 ns	5.50 ns	5.52 ns	5.50 ns	5.61 ns	5.57 ns	5.44 ns	x

n.s – not significant, * $p < 0{,}05$, ** $p < 0{,}01$ *A*,*B*,*C* – means of sowing systems (pure stand and with companion crops), *a*,*b*,*c* – interaction (sowing system x position in a crop rotation)

ished the C content in soil when compared with spring barley grown after potato (four-field crop rotations A and D). The biggest significant differences (by 1.13 g kg^{-1}) relative to both of these stands were noted under spring barley grown after potato in the crop rotation sequence with a 50% share of spring barley. The companion crop of Italian ryegrass decreased (by nearly 10%) the content of this element in a stand of spring barley where the spring barley after spring barley sequence was repeated twice; the difference was

Table 3

Content of carbon in the arable soil layer (0-20 cm) before the establishment (2005) and after the completion of the field experiment (2011), g kg^{-1} of dry mass soil

Years Stand type	Crop rotation with spring spring barley (%), preceding crop								Aver-age
	A - 25	B - 50		C - 50		D - 75			
	potato A	potato B1	spring wheat B2	spring wheat C1	spring barley C2	potato D1	spring barley D2	spring barley D3	
Pure stand									
2005	10.80	10.55	9.30	9.30	9.00	11.15	9.45	9.80	x
2011	10.50	9.37	9.50	9.58	9.45	10.50	9.90	9.39	x
t-Student	ns	ns	ns	ns	**	ns	*	ns	x
With Italian ryegrass companion crop									
2005	9.80	x	8.73	x	9.20	8.95	x	9.08	x
2011	10.15	x	9.90	x	9.30	9.35	x	9.14	x
t-Student	ns	x	ns	x	ns	ns	x	ns	x
With red clover companion crop									
2005	x	9.70	x	9.33	x	x	9.10	x	x
2011	x	9.56	x	9.52	x	x	9.18	x	x
t-Student	x	ns	x	ns	x	x	ns	x	x
2011									
Pure stand	10.50*a*	9.37*bc*	9.50*c*	9.58*bc*	9.45*c*	10.50*a*	9.90*b*	9.39*c*	9.82*A*
With Italian ryegrass companion crop	10.15*ab*	x	9.90*d*	x	9.30*c*	9.35*c*	x	9.14*cd*	9.37*B*
With red clover companion crop	x	9.56*bc*	x	9.52*c*	x	x	9.18*cd*	x	9.42*B*
Average	10.33**A**	9.65**BC**	9.20**C**	9.55**BC**	9.38**BC**	9.93**B**	9.54**BC**	9.27**C**	x

n.s – not significant, * $p < 0.05$, ** $p < 0.01$ **A**,**B**,**C** – means of sowing systems (pure stand and with companion crops), **A**,**B**,**C** – means of spring barley stands (*A* to *D*3), *a*,*b*,*c* – interaction (sowing system x position in a crop rotation)

significant relative to the sequence of spring barley after potato in crop rotation sequence A (the control).

The experimental factors significantly differentiated the soil content of phosphorus over the seven years (Table 4). In pure spring barley stands, compared to the soil chemical composition before the experiment (in 2005), the highest increase in the soil content of P (more than 1.5-fold) was noted in the stand of spring barley after spring wheat (crop rotation B). Consi-

Table 4

Content of available phosphorus P in the arable soil layer (0-20 cm) before the establishment (2005) and after the completion of the field experiment (2011), mg kg^{-1}of dry mass

Years Stand type	Crop rotation with spring spring barley (%), preceding crop								Average
	A - 25	B - 50		C - 50		D - 75			
	potato A	potato B1	spring wheat B2	spring wheat C1	spring barley C2	potato D1	spring barley D2	spring barley D3	
Pure stand									
2005	85.5	91.1	63.5	76.6	85.6	88.6	75.5	77.7	x
2011	83.7	92.1	105.2	93.2	93.1	97.0	96.0	97.4	x
t-Student	ns	ns	**	**	**	**	**	**	x
With Italian ryegrass companion crop									
2005	78.8	x	76.8	x	92.9	88.2	x	80.8	x
2011	84.4	x	79.4	x	95.6	89.3	x	98.9	x
t-Student	ns	ns	ns	ns	ns	ns	ns	**	x
With red clover companion crop									
2005	x	79.7	x	89.0	x	x	102.5	x	x
2011	x	84.5	x	90.6	x	x	97.0	x	x
t-Student	x	*	ns	ns	x	x	ns	x	x
2011									
Pure stand	83.7*ef*	92.1*d*	105.2*a*	93.2*cd*	93.1*cd*	97.0*bc*	96.0*c*	97.4*bc*	94.7*A*
With Italian ryegrass companion crop	84.4*e*	x	79.4*f*	x	95.6*c*	89.3*de*	x	98.9*b*	89.5*B*
With red clover companion crop	x	84.5*e*	x	90.6*d*	x	x	97.0*bc*	x	90.6*B*
Average	84.1**D**	88.2**CD**	92.3**C**	91.9**C**	94.4**B**	93.2**BC**	96.5**B**	98.2**A**	x

n.s – not significant, * $p < 0.05$, ** $p < 0.01$ *A*,*B*,*C* – means of sowing systems (pure stand and with companion crops), **A**,**B**,**C** – means of spring barley stands (A to D3), *a*,*b*,*c* – interaction (sowing system x position in a crop rotation)

derably more of this element in soil was also observed in response to the sequence of spring barley after spring barley in crop rotation D. The Italian ryegrass companion crop with the twice repeated sequence of spring barley after spring barley raised by over 18.0 g kg^{-1} the soil richness in P compared to the period before the experiment. In turn, among the plots with the red clover companion crop, significantly more P (by about 6%) was determined in soil under spring barley grown after potato in four-field crop rotation B.

In 2011, significantly more phosophorus (by nearly 5%) in soil was determined in pure stands than in plots with the companion crops (Table 4). Much more phosphorus was determined in soil under spring barley grown after potato in the Norfolk four-field crop rotation system (the control) than in all other stands of the tested cereal, with the highest significant differences (ca 21.5 g kg^{-1}) noted in soil under spring barley grown after spring wheat in crop rotation system B. Significantly less P (by 5.0 g $kg^{-1\ 1}$) was determined in soil with the Italian ryegrass companion crop (crop rotation B) than under spring barley grown after potato in the crop rotation with a 25% share of spring barley (the control). Most P in soil (98.9 g kg^{-1}) was determined in the twice repeated sequence of spring barley after spring barley in four-field crop rotation D, where the pool of P increased by 14.5 g kg^{-1} relative to the sequence of spring barley after potato in crop rotation A (the control). A higher concentration of P in soil (97.0 g kg^{-1}) was found under plots with the red clover companion crop in spring barley grown after spring barley (crop rotation D), whereas the sequence of spring barley after potato in the crop rotation system with a 50% share of spring barley (four-field crop rotation B) caused the opposite effect.

After the experiment was finished, in comparison with the soil chemical composition before the study was started in 2005, it was only spring barley in pure stand grown after potato in the control four-field crop rotation system that caused a significant decrease (by nearly 10%) in the soil content of K (Table 5). As for the other treatments, the effect on the soil concent of K was opposite. The highest significant differences (by 37.8 and 38.5%), in comparison with the perior before the experiment, were detected in soil under spring barley grown after spring wheat and after spring barley (crop rotations B and D). The smallest differences occurred in soil under spring barley grown after potato in the crop rotation with a 50% share of spring barley. In turn, no significant differences in the content of this element were determined in soil under the plots with the companion crops during the seven-year-long experiment.

In 2011, significantly more K was found in soil under pure spring barley than under spring barley with the companion crops (Table 6). Spring barley grown after spring barley in the crop rotation with a 50% share of spring barley caused a significant increase in the soil content of potassium in comparison with the sequences where spring barley followed potato or spring wheat in four-field crop rotations A, B and C. The biggest differences in the P content of soil (by 52 and 44 mg kg^{-1}) were found in soil under spring barley after potato in four-field crop rotations A and B. When Italian ryegrass was sown as an companion crop, most potassium (231 mg kg^{-1}) was determined in soil when spring barley followed spring barley (crop rotation C); the differences were 32 and 50 mg kg^{-1}, respectively, in comparsion with the treatments of the Norfolk crop rotation (the control treatment) and spring barley after spring wheat (crop rotation B). On the other hand,

Table 5

Content of available potassium K in the arable soil layer (0-20 cm) of soil before the establishment (2005) and after the completion of the field experiment (2011), mg kg^{-1} of dry mass

Years Stand type	Crop rotation with spring spring barley (%), preceding crop								Aver-age
	A - 25	B - 50		C - 50		D - 75			
	potato A	potato B1	spring wheat B2	spring wheat C1	spring barley C2	potato D1	spring barley D2	spring barley D3	
Pure stand									
2005	211.0	193.0	164.0	180.0	201.0	208.0	166.0	191.0	x
2011	190.0	198.0	226.0	208.0	242.0	229.0	230.0	230.0	x
t-Student	*	*	**	**	**	**	**	**	x
With Italian ryegrass companion crop									
2005	195.0	x	174.0	x	235.0	187.0	x	191.0	x
2011	199.0	x	178.0	x	231.0	192.0	x	193.0	x
t-Student	ns	x	ns	x	ns	ns	x	ns	x
With red clover companion crop									
2005	x	164.0	x	224.0	x	x	228.0	x	x
2011	x	172.0	x	222.0	x	x	227.0	x	x
t-Student	x	ns	x	ns	x	x	ns	x	x
2011									
Pure stand	190.0*c*	198.0*bc*	226.0*ab*	208.0*b*	242.0*a*	229.0*ab*	231.3*a*	230.3*ab*	219.1*A*
With Italian ryegrass companion crop	199.0*bc*	x	178.0*cd*	x	231.0*a*	192.0*c*	x	193.0*c*	198.6*C*
With red clover companion crop	x	172.0*d*	x	222.0*ab*	x	x	227.0*ab*	x	207.0*B*
Average	194.5**E**	185.0**F**	202.0**D**	215.0**C**	236.5**A**	210.5**C**	228.5**B**	211.5**C**	x

n.s – not significant, * $p < 0.05$, ** $p < 0.01$ *A*,*B*,*C* – means of sowing systems (pure stand and with companion crops), **A**,**B**,**C** – means of spring barley stands (A to D3), *a*,*b*,*c* – interaction (sowing system x position in a crop rotation)

cultivation of spring barley undersown with red clover on a stand after potato (crop rotation B), relative to spring barley after spring wheat and spring barley after spring barley in crop rotations C and D, significantly decreased the concentration of this element in soil, by 50.0 and 55.0 mg kg^{-1}, respectively.

After the experiment was completed, in comparison with the soil's chemical composition in 2005, significantly less Mg (by 2.80 mg kg^{-1}) was

Table 6

Content of available magnesium Mg in the arable soil layer (0-20 cm) before the establishment (2005) and after the completion of the field experiment (2011), mg kg^{-1} of dry mass

Years Stand type	Crop rotation with spring spring barley (%), preceding crop								Aver-age
	A - 25	B - 50		C - 50		D - 75			
	potato A	potato B1	spring wheat B2	spring wheat C1	spring barley C2	potato D1	spring barley D2	spring barley D3	
Pure stand									
2005	39.20	37.90	34.70	39.80	38.90	39.60	36.20	36.50	x
2011	36.40	36.90	38.00	38.90	35.90	48.40	36.80	37.30	x
t-Student	**	ns	ns	ns	ns	ns	ns	ns	x
With Italian ryegrass companion crop									
2005	37.00	x	38.30	x	46.40	45.20	x	48.10	x
2011	39.70	x	38.60	x	46.70	45.80	x	47.90	x
t-Student	ns	x	ns	x	ns	ns	x	ns	x
With red clover companion crop									
2005	x	38.50	x	47.40	x	x	46.60	x	x
2011	x	39.40	x	48.80	x	x	47.50	x	x
t-Student	x	ns	x	ns	x	x	ns	x	x
2011									
Pure stand	36.40*c*	36.90*c*	38.00*c*	38.90*bc*	35.90*c*	48.40*a*	36.80*c*	37.30*c*	38.58*B*
With Italian ryegrass companion crop	39.70*bc*	x	38.60*c*	x	46.70*ab*	45.80*b*	x	47.90*a*	43.74*A*
With red clover companion crop	x	39.40*bc*	x	48.80*a*	x	x	47.50*a*	x	45.23*A*
Average	38.05**C**	38.15**C**	38.30**C**	43.85**AB**	41.30**BC**	47.10**A**	42.15**BC**	42.60**B**	x

n.s – not significant, * $p < 0.05$, ** $p < 0.01$ *A*,*B*,*C* – means of sowing systems (pure stand and with companion crops), **A**,**B**,**C** – means of spring barley stands (A to D3), *a*,*b*,*c* – interaction (sowing system x position in a crop rotation)

determined in the soil under spring barley grown after potato in the Norfolk crop rotation system (pure stand). The companion crop of Italian ryegrass on the plot with the twice repeated sequence of spring barley after spring barley (crop rotation D) decreased the magnesium concentration in soil, while red clover as an companion crop in spring barley grown after potato, spring wheat and after spring barley (four-field crop rotations B, C and D) caused the opposite effect. However, the differences observed in the treatments with both companion crops were not confirmed statistically.

In 2011, significantly less Mg in soil was found under pure stands of spring barley than under plots of spring barley with companion crops (Table 6). Significantly more Mg was determined in soil of the plot cropped with spring barley after potato in the crop rotation with a 75% share of spring barley, than in the soil from the other spring barley treatments. The biggest differences in the content of Mg in soil (by 12 and 12.5 mg kg^{-1}) were determined in the soil under spring barley grown after potato and spring barley grown after spring barley (four-field crop rotations A and C).

The companion crop of Italian ryegrass in spring barley grown after potato (crop rotation A) most distinctly decreased the content of Mg in soil relative to the twice repeated sequence of spring barley after spring barley (crop rotation D). Furthermore, plots with the companion crop of red clover in spring barley cultivated after spring barley (four-field crop rotation D) were found to be significantly richer in soil magnesium than the plots where spring barley was grown after potato and the whole crop rotation system contained a 50% share of spring barley

A statistically significant dependence was determined in this study between the dry matter of the companion crops and the soil pH value (Table 7).

Table 7

Pearson's correlation coefficients between biomass of companion crops and soil pH as well as macronutrients within the tested crop rotations

Chemical properties	Crop rotation with spring spring barley (%), preceding crop							
	A - 25	B - 50		C - 50		D - 75		
	potato A	potato B1	spring wheat B2	spring wheat C1	spring barley C2	potato D1	spring barley D2	spring barley D3
pH	-0.19	-0.18	0.87*	-0.01	-0.20	0.15	0.84*	0.41
C org.	-0.53	0.01	-0.47	0.02	-0.30	0.14	0.70	0.13
P	0.19	-0.48	0.48	-0.48	-0.35	0.04	0.88*	0.04
K	0.12	-0.33	-0.63	0.20	-0.20	-0.43	0.43	-0.22
Mg	-0.57	0.07	0.49	-0.42	-0.27	-0.41	-0.86*	-0.32

* significance at $p < 0.05$

As the dry matter yield of Italian ryegrass grown as a companion crop increased, the soil pH increased under the stand of spring barley grown after spring wheat in crop rotation B (correlation coefficient 0.87). Similar relationships were determined for the soil under spring barley grown with a red clover companion crop where spring barley followed spring barley in four-field crop rotation D. In the plot cropped with spring barley after spring barley in the crop rotation system with a 75% share of spring barley (crop rotation D), a positive correlation was determined between the biomass of a red clover companion crop and the content of phosphorus in soil (correlation coefficient 0.88). In turn, a decrease in the dry matter yield of undersown red clover and the content of phosphorus in soil (correlation coefficient 0.88). In turn, a decrease in the dry matter yield of red clover companion crop raised the content of Mg in soil. No significant relationships were determined between the analysed characteristics under the other plots.

DISCUSSION

Excessive saturation of a crop rotation system with cereals has a negative influence on chemical properties of soil, causing a significant decline in soil fertility (Blecharczyk et al. 2005). Askegaard and Eriksen (2008) as well as Eriksen and Thorup-Kristensen (2002) claim that companion crops limit losses of nutrients in soil, and release them during decomposition, which has a beneficial effect on the growth and development of the subsequent crop.

In this study, after the termination of the field trials, it was only in plots cropped with spring barley after spring barley in the four-field crop rotation with a 50% share of spring barley (pure stand) that the soil pH was found to be significantly lower than before the experiment. In 2011, a significantly higher soil pH was noted under plots with companion crops. Likewise, Parylak (1996) under plots with perennial rygrass ploughed into soil found higher soil pH. In turn, Pałys et al. (2009) noted a significantly higher soil pH on plots with companion crops. Somewhat different results in this regard were reported by Jastrzębska (2009) as well as by Smagacz and Kuś (2010), who did not find any distinct changes in soil pH as induced by the way spring spring barley was sown or in correlation with the share of cereals in a crop rotation.

After the termination of the experiment (pure stand), in comparison with the year 2005, significantly more organic carbon was determined in soil under the stand of spring barley grown after spring barley (four-field crop rotations C and D), while the sequence of spring barley after spring barley in the crop rotation with a 50% share of spring barley significantly differentiated the above characteristic. Wanic et al. (2004) maintain that raising the contribution of spring barley in a crop rotation to 75% and growing once or twice spring barley after spring barley did not cause any depletion in soil humus. Similar results were reported by Smagacz, Kuś (2010), while Parylak et al. (2006), who conducted a field trial on light soil, determined that the content of organic carbon in cereal monocultures was lower by 4-9% than in a versatile crop rotation system.

In 2011, much more organic C in soil was determined under pure spring barley stands than under plots with companion crops. The tested plots of spring spring barley (pure sowing) decreased considerably the soil content of organic carbon in comparison to the sequence of spring barley after potato in the Norfolk crop rotation. Likewise, in their experiment Rychcika et al. (2006) found out that a versatile crop rotation system had a positive impact on the balance of organic matter in soil.

This experiment showed that Italian ryegrass as a companion crop significantly decreased the content of carbon under the plots with the twice repeated sequence of spring barley after spring barley in the crop rotation with a 75% share of spring barley, as compared to the sequence of spring barley after potato in the Norfolk crop rotation. N'Dayegamiye and Tran (2001) documented that companion crops raised the content of organic carbon in soil but did not have a considerable impact on its content of labile fractions of organic matter. Likewise, Pałys et al. (2009) concluded that serradelle, red clover and white clover increased the available C content in soil. In a study conducted by Blombäck et al. (2003), companion crops grown for 6 years only slightly (by about 2%) increased the content of organic matter in soil. In turn, Eichler-Loberman et al. (2008) demonstrated that companion crops did not change substantially the C abundance in soil during a three-year-long experiment. Similar results were obtained by Godsey et al. (2007) and Takata et al. (2008) and Wivstand et al. (2005). Liu et al. (2015) claim that companion crops during the plant growing season absorb nutrients from the soil and incorporate them in their plant tissues, which means that they can remove nutrients from the soil profile. Talgre et al. (2012) documented that most nutrients from soil are taken up by companion crops of pea and field bean. Campbell et al. (1999), Murphy et al. (2007) and Takata et al. (2008) maintain that the selection of crops, agricultural technologies and variability of the weather conditions during the plant growing period all have impact on the soil content of organic C.

Results of studies on crop rotation sequences and varied percentages of cereals in crop rotation systems on the soil content of available P, K, and Mg are not unequivocal (Eichler-Loberman et al. 2008, Constantin et al. 2010, Liu et al. 2015, Wanic et al. 2013).

In our field trial, among pure stands of spring barley, the highest rise in the soil content of P was observed when spring barley followed spring wheat in the crop rotation with a 50% share of spring barley, and when spring barley was sown after spring barley in crop rotation D. The companion crop of Italian ryegrass in spring barley in the twice repeated spring barley after spring barley sequence raised the P content in soil when compared to the soil's chemical composition prior to the experiment.

On the plots with red clover as a companion crop, significantly more P was determined in soil under spring barley grown after potato in four-field crop rotation B. In 2011, significantly more phosphorus in soil was determined under pure spring barley stands than under plots with the companion crops. Spring barley after potato in the Norfolk four-field crop rotation system considerably decreased the content of this element in soil. The companion crop of Italian ryegrass on a plot of spring barley sown after spring wheat (crop rotation B) decreased the soil content of P. A similar effect was caused by red clover as a companion crop in the sequence of spring barley after potato in the crop rotation with a 50% share of spring barley.

After the completion of the field experiment, relative to the parameters observed before it, spring barley (pure stand) after potato (the Norfolk four-field crop rotation system) significantly reduced the soil richness in K and Mg. The least potassium was determined in soil under spring barley grown after spring wheat and after spring barley in the crop rotations with a 50% and 75% share of spring barley.

In 2011, significantly more K and considerably less Mg were found in soil under pure spring barley than under spring barley plots with the companion crops. Spring barley after spring barley in the crop rotation with a 50% share of spring barley significantly raised the content of potassium in soil as compared to spring barley grown after potato or after spring wheat in crop rotations A, B and C. In turn, the spring barley stand after potato (crop rotation D) increased the concentration of magnesium in soil in comparison with the remaining spring barley stands. With respect to undersown Italian ryegrass, most K was determined in soil under spring barley sown after spring barley (crop rotation C), and the twice repeated cultivation of spring barley after spring barley increased the pool of magnesium in soil relative to its amounts in soil under the plot of spring barley grown after potato or after spring wheat in crop rotations A, B and D. In turn, spring barley undersown with red clover and grown on a plot after potato (crop rotation B), in comparison with the sequence of spring barley after spring wheat or spring barley after spring barley (crop rotations C and D), significantly decreased the concentration of this element in soil, while significantly more magnesium in soil was determined under spring barley plot spring wheat than after potato in the crop rotation with a 50% share of spring barley.

The results obtained in this study are partially consistent with results reported by other researchers. Pałys et al. (2009) demonstrated in their experiment that the twice repeated cultivation of spring barley with the companion crop of Westerworld ryegrass, in comparison with pure spring barley, decreased the content of P in soil. Liu et al. (2015) concluded that under unfavourable weather conditions companion crops accumulate from 7 to 10 kg of phosphorus and from 40 to 60 kg of potassium, while on poor soils they are not highly efficient fertilisers due to the low yield of biomass. According to Eichler-Löbermann et al. (2008), oil seed radish and ryegrass produce thrice as much biomass and accumulate twice as much P as serradelle and buckwheat. Constantin et al. (2010) claim that companion crops maintain the concentration of phosphates on a level below 50 mg l^{-1}. In turn, Jastrzębska (2009) confirmed small differences in the soil richness in P, K and Mg, depending on the type of sowing and degree of saturation of crop rotation with spring spring barley. Slightly different results in this regard were provided by Pałys et al. (2009). These authors, having ploughed into the soil white clover and Westerworld ryegrass grown as companion crops, determined a lower soil content of potassium, but did not note any changes in the soil content of magnesium.

CONCLUSIONS

1. After the termination of the experiment, in comparison with the soil condition in 2005, before the trials started, lower soil pH was determined under spring barley grown after spring spring barley in the crop rotation with a 50% share of spring spring barley. Neither of the companion crops differentiated the pH of the arable soil layer in any of the tested crop rotations.

2. After the termination of the experiment, spring barley cultivation (pure stand) in crop rotations of spring spring barley after spring barley with a 50% and 75% share of this cereal raised the soil content of organic carbon. Significantly more organic C was determined in soil under pure spring barley stands than under plots with the companion crops. In soil under spring barley grown after potato (pure stand) in crop rotations with a 50% and 75% share of spring barley, an increase in the soil carbon content was noted. Undersown Italian ryegrass significantly decreased the organic C content of soil under spring barley grown in the twice repeated spring barley after spring barley sequence in crop rotation D.

3. In the seven-year-long experiment, the highest increase in the soil content of P was noted under the spring barley stand after spring wheat in the crop rotation with a 50% share of spring barley. Growing spring barley with undersown Italian ryegrass where the spring barley after spring barley sequence was repeated twice and undersown with red clover following potato (crop rotation B) raised the richness of soil in P relative to the soil's content of this element prior to the experiment.

4. In comparison to the soil's chemical composition prior to the experiment, after its termination it was only spring barley (pure stand) grown after potato in the Norfolk four-field crop rotation system that significantly reduced the soil content of K. In 2011 among plots undersown with Italian ryegrass, the least K was noted under spring barley following spring wheat, while in plots undersown with red clover the lowest K content of soil occurred under plots of spring barley following potato.

5. After the experiment, less magnesium in soil was recorded under pure spring barley than with companion crops. However, most magnesium in soil was determined under a pure stand of spring barley after pottao (crop rotation D). Undersown Italian ryegrass and twice repeated spring barley after spring barley sequence raised the soil content of Mg the highest in compari-

son with the sequence of spring barley after potato in crop rotation A. Likewise, undersown red clover in spring barley grown after spring barley (crop rottaion D) increased the soil content of magnesium relative to the sequence of spring barley after potato in the crop rotation with a 50% share of spring barley.

6. As the biomass of undersown Italian ryegrass increased, the soil pH significantly rose under spring barley grown after spring wheat in crop rotation B. Concerning red clover as a companion crop, a similar situation appeared under spring barley cultivated after spring barley (crop rotation D). Under the plot of spring barley preceded by spring barley (crop rotation D) a positive correlation was identified between the biomass of undersown red clover and the content of phosphorus in soil, while a decrease in the biomass of this companion crop raised the content of Mg in soil.

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