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The introduction of soybean in an organic crop rotation in the Nemoral zone: the impact on subsequent spring wheat productivity

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Abstract

The sustainability of an organic crop rotation frequently depends on the residual effects of legume pre-crops. However, the contribution of legumes varies considerably depending on their species as well as local soil and climatic conditions. This research aims to compare the pre-crop effects of traditional grain and forage legumes with those of soybean (*Glycine max* (L.) Merr.), which is not widespread in Europe latitude 55° due to climatic constraints, on the productivity of subsequent cereals. A three-year (2016–2018) crop rotation was investigated using four pre-crops: spring barley, spring barley intercropped with red clover, pea and soybean. The effect of pre-crops on grain yield and quality and chemical composition of subsequently grown spring wheat was explored. Nitrogen (N) content in grain and straw, mineral nitrogen (N_{\min}) content in the soil were measured, the carbon to nitrogen (C:N) ratio and net N balance were calculated. The rotation was repeated twice and the results showed that pea and soybean did not produce sufficient biomass and amount of fixed N to maintain a stable positive residual effect in both rotation replications. Under favourable conditions, pea derived 66.1 kg ha⁻¹ N and soybean – 64.7 kg ha⁻¹ N from the atmosphere, while red clover intercropped with spring barley produced 65.4–82.7 kg ha⁻¹ N yearly. Most of the total N (N_{tot}) accumulated by pea and soybean plants, 69% and 80%, respectively, was removed with grain yield, while comparable percentages of N (59–68%) were left by the residues of red clover and spring barley mixture. As a result, the greatest effect on subsequently grown spring wheat was exerted by the mixture of spring barley and red clover (yield increase 354–1414 kg ha⁻¹). Comparing grain legumes, only efficiently nodulated soybean produced a positive +20.6 kg ha⁻¹ net N balance and increased the yield of spring wheat by 920 kg ha⁻¹. Pea resulted in the negative net N balance and increased the yield of spring wheat by 534 kg ha⁻¹. Mineral nitrogen in the soil increased under all legume pre-crops only in the second year of the crop rotation.

Key words: nitrogen, pea, pre-crop, red clover.

Introduction

Biological nitrogen (N) fixation by legumes is an important tool in organic farming, especially in stockless arable organic systems (Migliorini et al., 2014; Watson et al., 2017; Råberg et al., 2018), and has been perceived as a strategy to reduce the use of inorganic fertilizer and to decrease N import from conventional sources (Foley et al., 2011). Increasing the proportion of legume crops in a rotation, increases the proportion of N in the global nutrient cycles and also decreases the quantity of N lost from it (Seufert et al., 2012). At the ecosystem level, the net N gain due to N₂ fixation benefits the subsequent crops

and contributes to increased soil N fertility (Kumar, Goh, 2000; Janušauskaitė et al., 2013). Legume diversification increases the quantity, quality and chemical diversity of residues, in such a way that high diversity rotations can sustain soil biological communities and positively affect the soil organic matter (Tiemann et al., 2015).

Many studies have quantified rotational effects, often called pre-crop, break crop or residual effects (Angus et al., 2015; Feiziene et al., 2016; Grant et al., 2016). However, the N contribution by legumes varies considerably depending on their species as well as local

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soil and climatic conditions (Pandey et al., 2017). The most described legume yield stresses are excess or lack of precipitation (Nielsen, 2011; Cerezini et al., 2016). Insufficient water supply leads to retarded growth with short plant height, stunted flowering and pod set and thus reduced grain yield (Liu et al., 2008). Also, the total N (N_{tot}) accumulation by individual crop species varies in a wide range between different years and sites (Luce et al., 2015; De Notaris et al., 2019). Under European conditions, grain legume pre-crop effects are variable and increase cereal yields by 500–1600 kg ha⁻¹. Often, yield benefits of legumes to subsequent crops are the highest under low N fertilisation, and the N fertiliser rates can be reduced by on average 60 kg ha⁻¹ N with no significant yield penalty (Preissel et al., 2015).

In European countries, there is a limitation in use of animal manure from conventional farms in an organic crop rotation (Pandey et al., 2017). In such systems, production of grain legumes offers multiple environmental benefits and can enhance sustainability of European farming, but their production area is declining constantly (Preissel et al., 2015). The decrease in legume cultivation in most of European agriculture remains poorly understood (Iannetta et al., 2016), but legume production in Lithuania is currently increasing. Lithuania is among the leaders in European Union's field pea market with a high increase of pea acreage and production since 2015 (FAOSTAT, 2019, <http://www.fao.org/faostat/en/#data/QC/visualize>). It is therefore important to investigate pea in a crop rotation in the local climatic conditions, also to compare it with non-legume pre-crops (spring barley), forage legumes (spring barley + red clover) and non-traditional but high in demand grain legume – soybean (*Glycine max* (L.) Merr.). Soybean areas in Europe have been limited by climatic constraints until now, but considerable potential for development has emerged (de Visser et al., 2014) thanks to the availability of new superior varieties, developed under cool growing conditions of European Union (Zimmer et al., 2016). However, European soils are free of soybean specific rhizobia (Albareda et al., 2009) and should be inoculated by specific bacteria *Bradyrhizobium japonicum* (Cerezini et al., 2016).

In organic soybean production, establishment of an effective rhizobial symbiosis is therefore crucial for soybean production and overall soil fertility (Herridge, Rose, 2000; Batista, Dixon, 2019). The formation of root nodules, the process of N₂ fixation within nodules and the legume's subsequent reliance upon N₂ fixation for growth depend on many variables, such as the presence of effective rhizobial strains, soil acidity (pH), temperature, moisture and concentrations of nitrates (Chalk et al., 2010). The amounts of N₂ fixed by legumes are strongly related to legume biomass production and so is the residual effect in a crop rotation (Peoples et al., 2009; Unkovich et al., 2010).

In summary, grain legume pre-crop value is a crucial component of its farm-economic profitability in

European cropping systems, but further experimental research is required to ascertain its magnitude (Preissel et al., 2015). Developing an organic arable farming system, which is self-sufficient in N supply while maintaining high yields, is very important and also challenging. Little is known about how these different legume crops with different growth requirements and within different crop rotations contribute to the net N balance in an organic arable farming system with low or no external N input (Pandey et al., 2017). While pea investigations would give the evidence about its use in dominant crop rotations in cool temperate climate, less is known about how different soil and climatic conditions will affect N contributions by non-traditional species of legumes such as soybean in these systems.

The objectives of the present study were to: (1) quantify and compare the inputs of fixed N to rotational N cycle by soybean, field pea and red clover intercropped with barley, and (2) determine the impact of legume pre-crops on subsequent spring wheat grain yield and quality and N uptake.

Materials and methods

Experimental site and conditions. Field experiments were conducted at Institute of Agriculture (55°23'49" N 23°51'40" E), Lithuanian Research Centre for Agriculture and Forestry. The experimental site is situated in a temperate climatic zone which can also be referred to as Nemoral environmental zone, where the growing season lasts for 169–202 days. The experimental site is located above the northern boundary of typical soybean (*Glycine max* (L.) Merr.) distribution – 55°24' N, with reference to Ray et al. (2012), who defined typical soybean cultivation area in Europe to occur at up to the 49° N latitude. At the experimental site, the sum of active temperatures ($\Sigma T > 10^{\circ}\text{C}$) is 2100–2200°C, the annual precipitation totals 500–600 mm and the mean annual air temperature is 6.5°C. In 2016 and 2018, the temperature of the growing season was higher than the long-term average of 1980–2016. In 2016 and 2017, the spring was relatively dry, but summer unusually wet. In 2018, the summer was drier compared with the long-term average of the 1928–2016 period (Table 1).

The soil of the experimental site was a loamy *Endocalcaric Epigleyic Cambisol (Drainic, Loamic)* (WRB, 2014). Characteristics of the soil arable layer varied between the experimental years 2016 and 2017. Soil in the spring of 2016: acidity (pH) – 7.2 ± 0.5, humus – 2.3%, P₂O₅ – 93 mg kg⁻¹, K₂O – 156 mg kg⁻¹, mineral nitrogen (N_{min}) – 7.86 mg kg⁻¹; in the spring of 2017: pH – 7.0 ± 0.5, humus – 2.7%, P₂O₅ – 84 mg kg⁻¹, K₂O – 150 mg kg⁻¹, N_{min} – 11.6 mg kg⁻¹. Meteorological and soil chemical conditions show that the year 2017 was more favourable for pre-crops to grow than 2016 because of the two reasons. Firstly, in the spring of 2016 the water content in soil was lower because of the dry 2015, but in the spring of 2017, even with lower amount

Table 1. Monthly air temperature and precipitation during the growing seasons in 2016–2019

Month	Average air temperature °C				Sum of precipitation mm			
	AVG	2016	2017	2018	AVG	2016	2017	2018
January	-4.7	-8.0	-3.2	-1.6	31.1	35.9	14.2	55.5
February	-4.4	1.5	-1.6	-6.1	25.5	78.5	25.1	16.2
March	-0.7	1.9	3.5	-1.9	28.1	37.1	38.9	17.3
April	5.8	7.1	5.6	9.9	36.9	59.5	48.2	52.1
May	12.3	15.0	12.8	16.9	52.1	27.3	3.4	40.2
June	15.7	17.5	15.4	17.5	62.3	57.4	72.1	34.1
July	17.7	18.6	16.7	20.5	75.5	128.2	153.8	83.3
August	16.7	17.1	17.3	19.5	74.2	109.2	53.2	37.0
September	12.1	14.0	13.3	15.0	51.3	8.7	123.1	19.1
October	6.8	5.4	7.4	8.3	49.1	87.9	89.3	32.8
November	1.9	1.3	4.0	2.9	45.0	78.4	51.0	13.1
December	-2.3	0.9	1.0	-1.1	37.6	41.1	64.0	60.8

AVG – long-term average of the 1928–2016 period

of precipitation, the soil had extra moisture because of the wet 2016. Secondly, the N_{\min} after a dry year of 2015 was low in the spring of 2016, but in the spring of 2017 it was higher because of the dry 2016.

Experimental design and treatments. The experiment was repeated twice in three-year crop rotations of legume and cereal crops in 2016–2017 and 2017–2018 and was referred to as rotation A and B, respectively (Table 2). Four pre-crop species were used as treatments in the first year of the crop rotation: spring barley (SB), spring barley with red clover (SB + RC) intercropping, pea and soybean.

Table 2. Experimental design of the crop rotation replicated in time

1 st crop rotation replication (rotation A)		2016	2017
2 nd crop rotation replication (rotation B)		2017	2018
Treatments and crops:	1) spring barley, 2) spring barley + red clover, 3) pea, 4) soybean		spring wheat

The experiment was laid out in a randomized complete block design with four replications. Each plot was 3.0 m wide and 10.0 m long. All crops were sown with a disk drill at a 3 cm depth. Soybean cultivar ‘Merlin’, belonging to an early 000-maturity group, was sown on May 20 in 2016 and May 15 in 2017 at a seed rate of 120 kg ha⁻¹, was harvested on October 31 in 2016 and October 15 in 2017. Soybean seeds were inoculated with a *Bradyrhizobium japonicum* strain SEMIA5079 (=CPAC 15), containing 1.2×10^9 colony forming units (CFU) mL⁻¹. The dose of inoculant was calculated to deliver 1.2×10^6 cells per seed. The pea cultivar ‘Respect’ was sown on May 3 in 2016 and April 27 in 2017 at a seed rate of 300 kg ha⁻¹, was harvested on August 3 in 2016 and August 7 in 2017. The spring barley cultivar ‘Noja DS’ was sown on May 5 in 2016 and April 21 in 2017 at a seed rate of 220 kg ha⁻¹, harvested on August 5 in 2016 and August 14 in 2017. The red clover cultivar ‘Arimaičiai’ was intercropped in spring barley on May 5 in 2016 and May 7 in 2017 at a seed rate of 10 kg ha⁻¹, was cut twice per year on August 5 and October 5 in 2016 and on August 14 and October 23 in 2017. The spring wheat cultivar ‘Granary’ was sown on April 23 in 2016 and April 28 in 2017 at a seed rate of 230 kg ha⁻¹, was harvested on August 31 in 2016 and August 31 in 2017.

Table 3. The dry matter (DM) yield of grain and straw of the four pre-crops in the first year of the crop rotation

Treatment	Rotation A		Rotation B		
	grain yield	straw yield	grain yield	straw yield	
kg ha ⁻¹ DM					
Spring barley		1346 a	1782 cb	2395 b	1728 bc
Spring barley + red clover	spring barley	1197 a	1194 c	2137 b	1149 d
	red clover (1 st cut)	–	1418 c	–	1133 d
	red clover (2 nd cut)	–	2818 a	–	2051 b
Pea		1150 a	1350 c	3245 a	2647 a
Soybean		1622 a	2212 b	830 c	1226 cd

Note. Means followed by the same letters in the same column do not differ from one another ($p \leq 0.05$) according to Tukey test.

Significant interaction ($p < 0.001$) regarding grain and straw yield was found between years and treatments (Fig. 1). While field pea demonstrated the same trend as cereals, soybean failed to benefit from better growing conditions of 2017. The main reason was ineffective symbiosis of soybean with the applied *B. japonicum* bacteria in 2017. As a result, soybean grain yield decreased from 1622 to 830 kg ha⁻¹ DM and the

residues of legume plants were incorporated into the 0–10 cm soil layer by a disk cultivator and later in the autumn were ploughed down at the 25 cm depth. The first cut of red clover in the 2nd treatment was taken after spring barley harvesting, and the second cut was taken late in the autumn. The plots were harrowed in the spring before sowing of spring wheat as a subsequent crop. The experimental site was managed according to the rules of organic farming.

Data collection and analysis. Grain yield was measured while harvesting 3×10 m plots. The following grain quality traits were measured: 1000 kernel weight (TKW), content of protein, fat, moisture, glycemic index and grain density using a grain analyser Infratec 1241 (Foss, Denmark). Crop and straw yield was determined in 4×0.25 m² sampling areas in each plot. Soil samples for N_{\min} determination were taken in the spring, before sowing, from the 0–30 and 30–60 cm depths. The concentration of humus in the soil was determined by the Diameter method by an automatic analyser Vario EL (Elementar, Germany), N (g kg⁻¹) by the Kjeldahl method using a final photometric determination (UV/Vis Cary 50 Conc), P (g kg⁻¹) by the final photometric determination (UV/Vis Cary 50 Conc) and K (g kg⁻¹) by the atomic absorption method (atomic absorption spectrophotometer ANALYST 200, UK). Nitrogen fixation (N_{fix}) from the atmosphere was calculated using difference method (Herridge, Danso, 1995), where the main equation includes N contents of a non- N_2 -fixing plant (N_{nonfix}) grown in the same soil (plot) as the N_2 -fixing crop monoculture or mixture ($N_{\text{leg/mix}}$) / $N_{\text{fix}} = N_{\text{leg/mix}} - N_{\text{nonfix}}$. Total plant N was calculated by summing up N content of grain and residues / straw. Net N balance was calculated as follows:

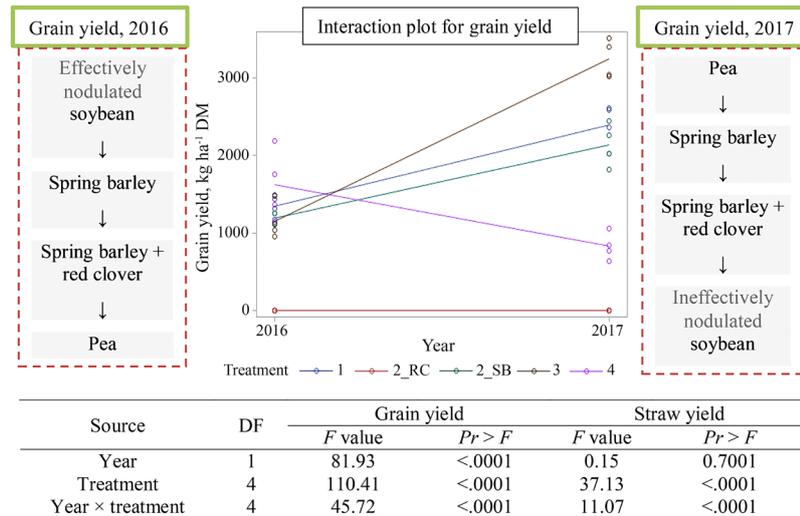
$$\text{net N balance} = \text{total plant N} - \text{N fixed} + \text{N of residues.}$$

Statistical analysis was performed using analysis of variance (ANOVA) on the statistical program SAS Enterprise, version 9.4 (SAS Institute Inc., USA). Homogeneity and normality were verified using Bartlett’s test. The interaction between years was tested. Means for significant effects were separated using Tukey multiple range tests at the 5% probability level ($P < 0.05$).

Results

Pre-crop value. Four species were cultivated as pre-crops in the organic crop rotation in 2016 and 2017 which are below referred to as rotation A and B, respectively. The value of pre-crops, estimated as accumulated yield of grain and straw, differed between the experimental years (Table 3).

yield of straw from 2212 to 1226 kg ha⁻¹ DM in 2016 and 2017, respectively (Table 3). Significantly similar ($p > 0.05$) amounts (1150–1622 kg DM ha⁻¹) of grain yield were accumulated by the four pre-crops in rotation A. Significantly higher amounts of straw were accumulated by soybean (2212 kg ha⁻¹) and red clover (4236 kg ha⁻¹) intercropped in spring barley. In rotation B, field pea produced 2.8 times more DM yield of grain than field



RC – red clover, SB – spring barley; DF – degree of freedom, *F* – value according to Fisher test, *Pr* – level of probability

Figure 1. The main effects and treatment and year interaction in relation to the dry matter (DM) yield (kg ha⁻¹) of grain and straw of the four pre-crop species

pea in rotation A, which was further significantly higher than that of the other three pre-crops in rotation B.

The N accumulation in grain was the highest (<0.01) for soybean plants (5.02–5.06% N) in both A and B rotations and the lowest for spring barley (1.61–1.76% N) (Table 4). Higher variation between years was found for N content in straw than in grains, depending on the efficiency of N fixation, 0.56–1.67% DM for soybean and 2.18–3.13% DM for red clover. Biomass of red clover

as a forage legume was distinguished by the narrowest carbon to nitrogen (C:N) ratio (14.8–22.0). The C:N in the straw of grain legumes, pea and soybean varied substantially between the two years. Under unfavourable growing conditions, the C:N of both pea and soybean straw was comparable to that of spring barley straw. Conversely, under more favourable conditions the C:N in pea and soybean straw was 1.5–2.6-fold higher.

Table 4. Nitrogen (N) and carbon (C) accumulated in the grains and straw of the pre-crops in the first year of the crop rotations, % dry matter

Treatment	Rotation A				Rotation B			
	N grain	N straw	C straw	C:N straw	N grain	N straw	C straw	C:N straw
Spring barley	1.65 b	0.54 c	52.6 b	97.0 a	1.76 c	0.74 c	49.4 a	67.4 b
Spring barley + red clover	1.61 b	0.55 c	52.8 b	97.8 a	1.69 c	0.65 cd	49.7 a	76.3 ab
red clover (1 st cut)	–	2.66 a	47.1 a	17.7 c	–	3.13 a	46.1 a	14.8 d
red clover (2 nd cut)	–	2.18 a	48.0 a	22.0 c	–	2.84 b	49.5 a	17.5 d
Pea	2.77 c	0.62 c	50.3 b	81.8 a	3.00 b	0.90 c	48.6 a	54.0 c
Soybean	5.02 a	1.67 b	51.3 b	32.4 b	5.06 a	0.56 d	48.3 a	86.5 a

Note. Means followed by the same letters in the same column do not differ from one another (*p* ≤ 0.05) according to Tukey test.

The total plant N yield was the highest in the pre-crop of spring barley intercropped with red clover (119.6–137.6 kg ha⁻¹), but significantly similar amount of N was accumulated by soybean in rotation A (118.9 kg ha⁻¹) and pea in rotation B (121.1 kg ha⁻¹) (Fig. 2). Most of the total N accumulated by pea and soybean plants, 69% and 80% respectively, was removed with grain yield, while comparable percentages of N (59–68%) were left by the residues of red clover and spring barley mixture. This determined the highest positive net N balance (+33.3

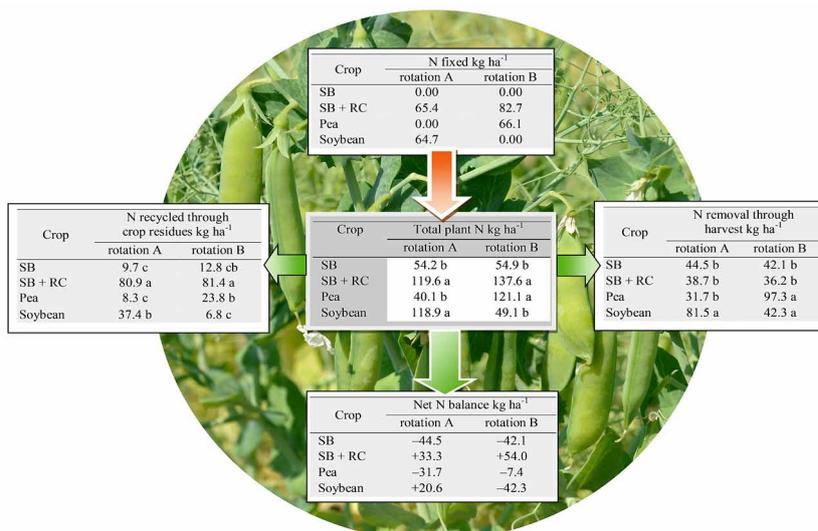
and +54.0 kg ha⁻¹) in spring barley and red clover pre-crop. Grain legumes investing high levels of N in seed production had negative net N balance, except for effectively nodulated soybean in rotation A.

Pre-crop effect on subsequent crop. Spring wheat, cultivated in subsequent year after four pre-crops, produced significantly different yields of grain, the highest being after spring barley and red clover pre-crops in both A and B rotations (Table 5). It produced 354–1414 kg ha⁻¹ higher yield than sole spring barley.

Table 5. Spring wheat aboveground biomass, yield and grain traits

Treatment	Grain yield kg ha ⁻¹	Biomass g m ⁻²	Glycemic index	Protein %	Starch %	TKW g	Density kg hl ⁻¹
Rotation A							
Spring barley	1243 c	364 b	18.7 b	10.7 b	68.3 a	29.7 b	65.6 b
Spring barley + red clover	2657 a	593 a	20.1 a	11.7 a	67.2 b	32.9 a	67.6 ab
Pea	1777 bc	455 ab	19.4 a	11.2 a	67.7 ab	32.2 a	67.7 ab
Soybean	2163 ab	495 ab	19.7 a	11.2 a	67.8 ab	33.4 a	69.2 a
Rotation B							
Spring barley	1932 b	494 ab	16.9 b	9.8 b	69.1 a	43.9 a	81.3 ab
Spring barley + red clover	2286 a	558 a	19.7 a	10.9 a	68.4 a	43.8 a	82.3 a
Pea	1984 b	499 ab	16.9 b	9.9 b	68.9 a	43.8 a	81.0 b
Soybean	1895 b	458 b	16.8 b	9.9 b	68.9 a	43.2 a	81.3 ab

Note. TKW – 1000 kernel weight; means followed by the same letters in the same column do not differ from one another (*p* ≤ 0.05) according to Tukey test.



Note. SB – spring barley, RC – red clover; means followed by the same letters in the same column do not differ from one another ($p \leq 0.05$) according to Tukey test.

Figure 2. Allocation of the total plant nitrogen (N) to shoots and grains, N fixed and net N balance in the first year of the crop rotation

Grain legumes, pea and soybean, resulted in significantly higher grain yield of spring wheat by 534 and 920 kg ha⁻¹ only in rotation A. In addition, in rotation A, all legume pre-crops gave significant increase in protein content (by 5–9%), glycemic index (by 4–7%) and 1000 kernel weight (by 8–10%) of spring wheat. However, in rotation B, only red clover intercropped in spring wheat could significantly enhance protein content and, consequently, glycemic index of spring wheat.

In order to evaluate aftereffect of pre-crop legumes on subsequent winter wheat, which was grown after spring wheat in the third year of the crop rotation,

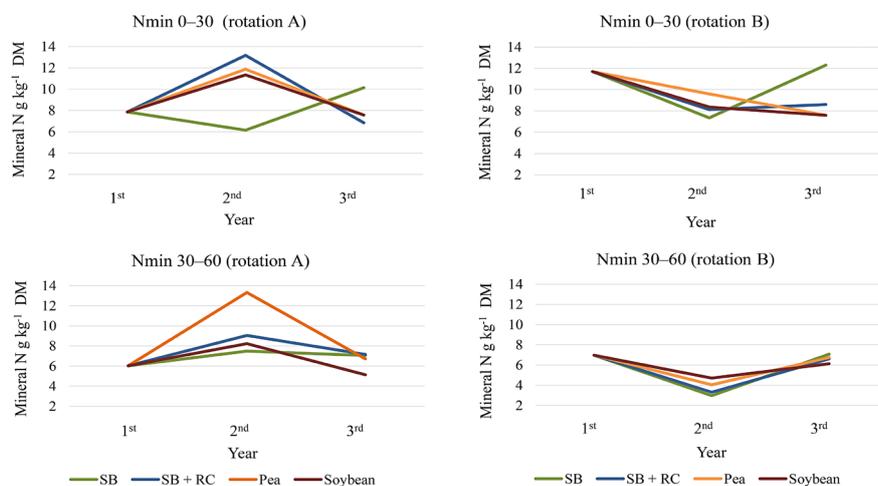
the main characteristics of spring wheat residues were assessed. The content of N and C and C:N of straw did not differ significantly among the treatments in both rotations. However, straw weight was significantly higher for spring wheat cultivated after spring barley intercropped with red clover, as well as after soybean pre-crop in rotation A, compared with sole spring barley (Table 6). In rotation B, no significant differences were detected.

Mineral N (N_{min}) in the rotation. The N_{min} content in the soil varied from 3 to 14 g kg⁻¹ N DM, showing time related effect of legume pre-crops through the three-year long crop rotation (Fig. 3).

Table 6. Yield, carbon (C) and nitrogen (N) content, C to N ratio of straw of spring wheat

Treatment	Rotation A				Rotation B			
	straw yield g m ⁻²	N % DM	C % DM	C:N	straw yield g m ⁻²	N % DM	C % DM	C:N
Spring barley	179 b	0.447 a	50.3 a	113 a	301 ab	0.328 a	52.6 a	163 a
Spring barley + red clover	270 a	0.488 a	50.6 a	105 a	329 a	0.410 a	51.4 a	127 a
Pea	223 ab	0.491 a	51.2 a	106 a	301 ab	0.320 a	51.9 a	166 a
Soybean	243 a	0.442 a	49.9 a	113 a	268 b	0.321 a	51.1 a	160 a

Note. DM – dry matter; means followed by the same letters in the same column do not differ from one another ($p \leq 0.05$) according to Tukey test.



DM – dry matter; SB – spring barley, RC – red clover

Figure 3. Mineral nitrogen (N) content in the soil, measured in the spring in crop rotations A and B at 0–30 and 30–60 cm depths

In the spring of 2017, which was the second year in crop rotation A and first year in crop rotation B, the mineral N was higher in the deeper (30–60 cm) soil layer due to high precipitation in the previous year and high content of moisture in the soil, which favoured N mineralisation in the soil. In the soil depth of 0–30 cm, the increase of N_{\min} was observed in the second year of the rotation after all legume pre-crops. However, this effect was not apparent in the spring of the third year, when the control treatment with spring barley showed higher amounts of N_{\min} compared with legumes in both rotations. The decrease of mineral N in the second year of the rotation and increase in the third year after spring barley pre-crop could be explained by a high C:N of the residues. A similar time related trend was noticed in the deeper 30–60 cm soil layer, and a substantial increase of N_{\min} in the second year was observed for all legumes, especially for pea pre-crop.

Discussion

Introduction of soybean in the cropping system. In order to optimize management of pests, weeds and diseases and to exploit nutrient availability, crop rotation should incorporate species with different life cycles, growth habits, root architectures and pest spectra (Reckling et al., 2016). Legume incorporation into a rotation could benefit as a break-crop; however, the domination of one legume species does not provide all spectrum of possible benefits. Pea is the most widely grown grain legume in Europe (FAO, <http://www.fao.org/faostat/en/#data/QC/visualize>); therefore, soybean introduction in European Union's cropping systems would beneficially impact the environment of the agro-ecosystem and also would satisfy the socio-economic needs (Nemecek et al., 2008). Our study showed that in a less favourable year with lower mineral N in the soil, the effectively nodulated soybean can produce a yield of 1622 kg ha⁻¹, which is higher than that of field pea and spring wheat in the organic farming system. Similar cultivars grown on commercial farms in Sweden had a reported yield of 1500–2400 kg ha⁻¹ (Fogelberg, Fogelberg, 2013). Average soybean yield in organically managed trials in Germany was reported as 1634 kg ha⁻¹ in the 2012–2013 seasons (Zimmer et al., 2016). In Poland, average soybean yield in 2015 was 1600 kg ha⁻¹ (Wenda-Piesik, Kazek, 2016). Average seed yield worldwide is 2300 kg ha⁻¹ (Bujak, Frant, 2009). All these data confirm the feasibility of soybean cultivation in a cool temperate climate of the Nemoral zone.

Biological N fixation varies in relation to the ability of legume species to fix N in different environmental conditions (Peoples et al., 2009). Across varying pedoclimatic regions of Europe it was shown that biological N fixation for different legume species ranges from 32 to 115 kg ha⁻¹ annually (Iannetta et al., 2016). Our results show that the allocation of biologically fixed N in straw differed between forage and grain legumes. Forage as opposed to grain crops in this range maintain high outputs of biomass and N_{tot} (Iannetta et al., 2016). In Baltic region, clover was shown to accumulate up to 6.4–14.9 t ha⁻¹ DM yield biomass and up to 118–327 kg ha⁻¹ of N (Ingver et al., 2019). Forage legumes use N to produce dry shoot matter more efficiently than grain legumes, whereas accumulation of N in grains is greater for grain legumes (Iannetta et al., 2016). Therefore, the residual effect is reduced when higher N amount is lost through harvest for grain legumes (Espinoza et al., 2012). Our data show that 69% and 80% of N_{tot} was accumulated in harvest and removed from the ecosystem in the case of soybean and pea, while as much as 59–68% of N was left in the soil by the residues of red clover and spring barley mixture.

By comparing species by species, it was demonstrated that clover has higher N fixation potential than pea. The proportion of N_2 derived from the atmosphere (%) is also significantly higher for white

clover (90%) than pea (69%) (Kumar, Goh, 2000). Pandey et al. (2017) showed that N_2 derived from the atmosphere in the aboveground biomass of red and white clover, grown in mixtures can be close to 100%, whereas derived N of grain legumes ranged between 61% and 95% in Denmark (Pandey et al., 2017). Unkovich and Pate (2000) suggest ranking principal crop legumes according to the quantities of N_2 fixed in the following descending order: soybean, lupin, field pea, faba bean, common bean, lentil and chickpea. Under European conditions, field pea was determined to gain 75% of total crop N, amounting to 150 kg shoot N ha, through N_2 fixation (Jensen, 1996). In other regions, soybean was reported to have higher effect than pea. Rochester et al. (2001) showed that soybean can fix 453–488 kg ha⁻¹ N per year and contribute 155–280 kg ha⁻¹ fixed N to the soil after seed harvest. However, soybean pre-crop value in Europe latitude up to 55° has not been widely investigated before, and there is a lack of evidence of soybean benefits, particularly advantages over pea in an organic cropping system. Our data show that effectively nodulated soybean can fix similar amounts of N as pea crop in a favourable year, but the net N balance is higher when growing soybean and also the impact on subsequent crop is higher than that of pea, which showed negative N balance in both years.

Nevertheless the pea with negative N balance managed to improve the yield of subsequent plant by 534 kg ha⁻¹ compared with spring barley. This could be explained by a range of other benefits of legumes not only through biological N fixation and enhanced soil N status (Iannetta et al., 2016). Some other factors are influencing yield positively, implying a cascade effect on other soil and system processes (Ehrmann, Ritz, 2014). This pre-crop benefit of grain legumes can lead to yield increases of up to 1600 kg ha⁻¹ in subsequent cereals (Preissel et al., 2015).

The influence of soybean on spring wheat productivity. The N contribution of a legume to subsequent crops is difficult to predict and is dependent on the specific legume, since legume species vary in their ability to biologically fix N_2 (Peoples et al., 2009). Moreover, the N contribution of legumes may vary over the years and sites due to variations in environmental conditions and soil properties, which affect the degree of N_2 fixation, legume grain yields and the quantity and quality of crop residues (Luce et al., 2015). This is consistent with our own study which assessed the pre-crop benefits of grain legumes at two replicates of crop rotation in time. It was revealed that in unfavourable conditions when the rate of N_2 fixation is low the effect of legumes does not differ from that of non-legume pre-crops. Also the effect of grain legume pre-crop was more apparent when the productivity of all crop rotation was low because of the environmental conditions, otherwise, in better conditions, this effect did not differ significantly. However, the positive effect of forage legume pre-crop (red clover + spring barley) was more consistent due to higher stability in agroecosystems and lower sensitivity to local climatic variability (Stoddard, 2013).

Studies have shown that conventional forage and grain legumes can increase the productivity of subsequent crops (Sarūnaitė et al., 2013; Feiziene et al., 2016). Since soybean is not a traditional crop in mid-Northern part of Europe, its residual effect is difficult to predict. Inadequate crop management technologies and lack of experience have been identified as constraints for soybean expansion in this region. Improving yield, yield stability, quality and biotic stress resistance are the main aims for soybean introduction in a new region (Albareda et al., 2009). For optimal N fixation, accumulation and production in an organic ecosystem, inoculation is an advisable agricultural practice when there are no specific rhizobia in the soil (Catroux et al., 2001). This is a common situation in most European soils. However, there is a paucity of knowledge about the efficiency of specific *Rhizobia* strains for soybean under environmental

conditions of Baltic-Nordic region in Europe. It is only known that N_2 derived from the atmosphere and total N_2 fixation of soybean vary significantly due to the variation of environmental conditions (Peoples et al., 1995), which highly impacts the nodulation, grain yield and residual effects (Deaker et al., 2004). In agreement, our results demonstrated that effectively nodulated soybean produced 1622 kg ha^{-1} grain yield and promoted significant residual effect on subsequent crop, while ineffectively nodulated soybean produced 830 kg ha^{-1} grain yield with no significant effect on subsequent crop.

Conclusions

1. The effect of grain legume pre-crops, soybean and pea, was not stable due to the varying weather conditions. Only in favourable conditions pea derived 66.1 kg ha^{-1} and soybean 64.7 kg ha^{-1} N from the atmosphere, while red clover intercropped with spring barley produced $65.4\text{--}82.7 \text{ kg ha}^{-1}$ N yearly.

2. Most of the total nitrogen (N) accumulated by pea and soybean plants, 69% and 80% respectively, was removed with grain yield, while comparable percentages of N (59–68%) were left by the residues of red clover and spring barley mixture. Therefore, the greatest effect on subsequently grown spring wheat was exerted by the mixture of spring barley and red clover (yield increase $354\text{--}1414 \text{ kg ha}^{-1}$ compared with sole spring barley).

3. The residual effect of soybean on subsequent wheat crops was greater than that of pea. Efficiently nodulated soybean produced positive $+20.6 \text{ kg ha}^{-1}$ net N balance and increased the yield of spring wheat by 920 kg ha^{-1} . Pea resulted in the negative net N balance but managed to increase the yield of spring wheat by 534 kg ha^{-1} through other soil and ecosystem processes not related to N.

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Gauruotosios sojos įjungimas į ekologinę sėjomainą nemoralinėje zonoje: įtaka po jų augintų vasarinių kviečių produktyvumui

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Santrauka

Ekologinės sėjomainos tvarumas dažnai priklauso nuo pupinių augalų priešėlių liekamojo efekto. Tačiau pupinių augalų indėlis labai skiriasi priklausomai nuo jų rūšies, taip pat vietinio dirvožemio ir klimato sąlygų. Tyrimo tikslas – palyginti tradicinių grūdinių ir žolinių pupinių augalų įtaką po jų augintų kviečių produktyvumui su gauruotosios sojos (*Glycine max* (L.) Merr.), kuri nėra plačiai paplitusi Europos 55° *platumos klimato sąlygomis*. Trejų metų trukmės sėjomaina buvo tirta auginant keturis priešėlius: vasarinius miežius, vasarinius miežius su raudonųjų dobilų išėliu, sėjamuosius žirnius ir gauruotąsias sojas. Buvo tirta priešėlio įtaka vėliau augintų vasarinių kviečių derliui, jo kokybei ir cheminei sudėčiai. Nustatytas azoto (N) kiekis grūduose ir šiauduose, mineralinio azoto kiekis dirvožemyje, taip pat apskaičiuotas C:N santykis ir suminis N balansas. Sėjomaina buvo kartota du kartus. Eksperimento rezultatai atskleidė, kad grūdinių pupiniai augalai žirniai ir sojos sukaupė nepakankamą kiekį biomasės ir fiksuoto azoto, kad būtų išlaikyta stabili teigiama augalinių liekanų įtaka abiejuose sėjomainos rotacijos pakartojimuose. Tik esant palankioms sąlygoms žirniai iš atmosferos sukaupė 66,1 kg ha⁻¹ N, sojos – 64,7 kg ha⁻¹ N, o raudonieji dobilai, sėti su vasariniais miežiais, kasmet sukaupė 65,4–82,7 kg ha⁻¹ N. Žirniai ir sojos 69 ir 80 % viso azoto sukaupė grūduose, o raudonųjų dobilų ir vasarinių miežių mišinys 59–68 % – augalinėse liekanose. Todėl vėliau augintiems vasariniams kviečiams didžiausią įtaką padarė vasarinių miežių ir raudonųjų dobilų mišinys – gautas 354–1414 kg ha⁻¹ derliaus priedas. Palyginus grūdinius pupinius augalus, tik efektyviai gumbelius formuojančios sojos turėjo teigiamą suminį N balansą (+20,6 kg ha⁻¹) ir vasarinių kviečių derlingumą padidino 920 kg ha⁻¹. Žirniai turėjo neigiamą suminį N balansą ir vasarinių kviečių derlingumą padidino 534 kg ha⁻¹. Dirvožemyje mineralinio azoto kiekis padidėjo auginant visus pupinių augalų priešėlius, tačiau tik antraisiais sėjomainos metais.

Reikšminiai žodžiai: azotas, priešėlis, raudonieji dobilai, žirniai.