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The long-term effect of legumes as forecrops on the productivity of rotation (winter rape-winter wheat-winter wheat) with nitrogen fertilization

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Abstract: A field experiment was carried out in the years 2012–2018 in Poland in a split-plot design. The aim of the study was to determine the long-term effect of legumes as forecrops on the productivity of rotation with nitrogen fertilization. The rotation included: legumes + spring barley (SB), winter rape (WR), winter wheat (WW) and winter wheat. The study was conducted as a two-factorial field experiment with four replications. The present study showed that legumes as forecrops increased the yield of all after-harvest crops in rotation. Yielding of these crops also depended on nitrogen fertilization and position in the rotation. After comparison of the influence of nitrogen fertilization on yield of cereals, it was observed that the effect of this factor was greater for WW cultivated in the fourth year of rotation than for WW cultivated in the third year of rotation. In relation with control, each dose of nitrogen fertilization caused a significant increase of WR and cereals yield, but the dose of 180 kg N/ha did not increase yield significantly in comparison to the dose of 120 kg N/ha. There was also negative agronomic N-efficiency observed between doses of 120–180 kg N/ha, which means that it is not necessary to use 180 kg N/ha, especially if there are legumes in crop rotation.

Keywords: *Hordeum vulgare* L.; *Brassica napus* L.; *Triticum aestivum* L.; after-effect of Fabaceae; mineral nutrition

In the last years, the European Community gave strong political support to the cultivation of cereals for food and animal feed production. In 2016, the harvested production of cereals (including rice) was around 301 million tonnes. Common wheat and spelt, grain maize and corn-cob-mix (CCM) and barley accounted for a high share (85.4% in 2016) of the cereals produced in the EU-28. France accounted for around a fifth of the EU-28 cereal production in 2016. France (18.0%), Germany (15.1%) and Poland (9.9%) together contributed to 43% of the EU total (Eurostat 2017/2018).

Consequently, most European plant protein requirements are covered by imports (Voisin et al. 2014). This model of agricultural production is connected with some environmental problems, but increasing the legumes cultivation in Europe could be a promising alternative. According to Nemecek et al. (2008) the strength of the introduction of grain legumes into intensive crop rotations with a high proportion of cereals and in the EU-28 intensive N-fertilizations, leads to the reduction of energy demand, global warming potential, ozone formation and acidification as well as eco- and human toxicity per unit of cultivated area. The main reasons for this are the absence of N-fertilizers for grain legumes, a reduced application of N-fertilizers to the following crop, improved possibilities for using reduced tillage techniques and greater diversification of the crop rotation, which helps to reduce problems with weeds and pathogens and limits pesticide applications. The aim of the study was to determinate a long-term effect of legumes as forecrops on the productivity of rotation with nitrogen fertilization.

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Table 1. Crop rotation in 2012–2017

2012	2013	2014	2015	2016	2017	2018
legumes + SB	WR	WW[1]	WW[2]	–	–	–
–	legumes + SB	WR	WW[1]	WW[2]	–	–
–	–	legumes + SB	WR	WW[1]	WW[2]	–
–	–	–	legumes + SB	WR	WW[1]	WW[2]

[1]winter wheat cultivated in the third year of rotation; [2]winter wheat cultivated in the fourth year of rotation. SB – spring barley; WR – winter rape; WW – winter wheat

MATERIAL AND METHODS

A field experiment was conducted at the Złotniki Research Station in the Wielkopolska region (52°29'N, 16°49'E, Poland) in Central Europe. The crop rotation included: legumes + spring barley (SB); winter rape (WR); winter wheat (WW) and winter wheat (Table 1). The study was conducted over 7 years (2012–2018) as a two-factorial field experiment with four replications and a split-plot design. The experiment included two factors. The first factor was forecrop (F) with the following levels: yellow lupin (indeterminate cv. Mister; YL); yellow lupin (determinate cv. Perkoz; YL); narrow-leaved lupin (indeterminate cv. Zeus; BL); narrow-leaved lupin (determinate cv. Regent; BL); white lupin (indeterminate cv. Butan; WL); pea cv. Tarchalska (PEA) and spring barley cv. Antek. The second factor was nitrogen fertilization of WR and WW: 0 kg N/ha (control); 60 kg N/ha (60); 120 kg N/ha (60 + 60) and 180 kg N/ha (60 + 60 + 60).

The study was conducted as a stationary experiment and at the same location for each year on the grey-brown podsolic soil (pH = 4.8 measured in 1 mol/dm^3 KCL; organic carbon 75.4 mg/100 g soil; 50–110 mg P/kg, 115–195 mg K/kg). The content of phosphorus and potassium was determined by the Egnera-Riehma method according to the norms PN-R-04023:1996 and PN-R-04022:1996. Sowing and harvest dates depended on species and weather conditions. The recommended sowing standards for seeds capable of germination were: 100 pieces per 1 m^2 for lupin indeterminate cultivars and PEA, 115 pieces per 1 m^2 for lupin determinate cultivars, 400 pieces per 1 m^2 for SB and WW, 45 pieces per 1 m^2 for WR. The area of forecrops plots was 70.6 m^2. Every year the pre-crop for legumes + SB was WW, after which glyphosate herbicide was used, in autumn after the harvest of pre-crop, at a rate of 2.5 L/ha. The soil was ploughed and harrowed. Phosphorus and potassium fertilization was uniform for all crops in rotation and each year it was applied in autumn (80 kg P/ha, 100 kg K/ha). There was no nitrogen applied to legume plants. A rate of 60 kg N/ha was applied once in spring before sowing SB. After harvesting forecrops and carrying out of necessary post-harvest and pre-sowing tillage treatments, each of forecrops plots was divided into smaller plots because of the second factor. The area of each plot for WR and WW was 14.5 m^2. Nitrogen fertilization rates (NH_4NO_3; N 34%) for WR were as follows: 60 kg N/ha early spring (before vegetation starting); 120 kg N/ha (the second rate was applied during stem elongation); 180 kg N/ha (the third rate was applied during flowering). WW nitrogen fertilization

Table 2. The Sielianinov's index in the vegetation periods for years 2012–2018 (recorded at the Agrometeorological Observatory in Złotniki, Poland)

Year	March	April	May	June	July	August	September	October
2012	0.68	0.92	1.24	2.62	2.53	1.00	0.72	1.27
2013	3.50	0.72	1.81	2.04	0.76	0.76	2.01	0.51
2014	1.01	1.81	2.25	0.89	0.70	1.68	1.00	0.40
2015	0.36	1.34	1.10	0.57	0.91	2.74	0.54	1.08
2016	4.27	1.45	0.90	1.52	2.55	0.75	0.11	4.23
2017	2.36	1.85	1.34	1.31	3.00	1.40	1.14	2.79
2018	11.83	0.94	0.33	0.46	1.12	–	–	–

Sielianinov's index (K): < 0.5 – drought; 0.5–1.0 – semi-drought; 1.0–1.5 – optimal moisture; > 1.5 – excessive moisture

https://doi.org/10.17221/556/2018-PSE

Table 3. The yield of winter rape depending on the forecrop and nitrogen (N) fertilization (t/ha)

Forecrop (F)		N dose (kg N/ha)				Mean
		0	60	60 + 60	60 + 60 + 60	
Yellow lupin	cv. Mister	4.6	4.7	4.9	4.8	4.8^{A} (+17.1%)
	cv. Perkoz	4.6	4.7	4.9	4.9	4.8^{A} (+17.1%)
Narrow-leaved lupin	cv. Zeus	4.2	4.5	4.7	4.8	4.6^{AB} (+12.2%)
	cv. Regent	4.2	4.5	4.6	4.6	4.5^{B} (+9.8%)
White lupin		4.3	4.3	4.5	4.7	4.4^{B} (+7.3%)
Pea		4.2	4.7	4.6	4.7	4.6^{AB} (+12.2%)
Mean for legumes		4.4	4.6	4.7	4.8	4.6 (+12.2%)
Spring barley		3.6	3.9	4.3	4.6	4.1^{C} (100%)
Mean		4.2^{c} (100%)	4.5^{b} (+7.1%)	4.7^{a} (+11.9%)	4.7^{a} (+11.9%)	4.5

Means denoted by the same letters for each factor did not differ significantly. *LSD* (least significant difference) F/N = 0.33; N/F = 0.32

rates (NH_4NO_3; N 34%) were as follows: 60 kg N/ha (early spring, before vegetation starting); 120 kg/ha (the second rate was applied during straw shooting phase); 180 kg N/ha (the third rate was applied during earing). During growing season, pesticides specified for particular biotic harmful organisms were used. The seed yield per 1 ha was calculated for legumes and cereals and for WR for 15% and 8% moisture, respectively.

The hydrothermal coefficient (K) of water supply according to the Sielianinov´s index, for individual years is shown in Table 2. The following formula was applied:

$$K = \frac{M_o \times 10}{D_t \times days}$$

Where: K – hydrothermal coefficient for individual months; Mo – total monthly precipitation; D_t – mean daily temperatures in a particular month.

There were considerable differences in the conditions of growth and development of the analysed species in individual years of the research. On average, during the whole growth period, 2014, 2015 and 2018 were the least favourable years due to low hydrothermal coefficients. However, it is noteworthy that extremely dry vegetation season was observed in 2018, which contributed to the lowest WW seed yield obtained throughout the research. Conditions of WR and WW growth and development in autumn in all research years were generally beneficial.

All data were processed using the analysis of variance (ANOVA) with the SAS package (SAS Institute, 1999). The obtained results were tested to a 2-way analysis of variance in a split-plot design. The least significant difference (*LSD*) was verified with the Tukey's test at the significance levels of $P < 0.01$ and $P < 0.05$. Means in tables denoted by the same letters for each factor did not differ significantly. Agronomic N-efficiency was calculated according to the following formula (Rathke et al. 2006):

$$\text{Agronomic N-efficiency (kg grain/kg N)} = \frac{\text{Seed yield}_{\text{fertilized}} - \text{seed yield}_{\text{unfertilized}}}{\text{N supply}}$$

RESULTS

The average grain yield of WR was 4.5 t/ha (Table 3). Nitrogen fertilization did not increase yields of WR cultivated after cvs. YL Mister and Perkoz. The dose of 120 kg N/ha and 180 kg N/ha increased signifi-

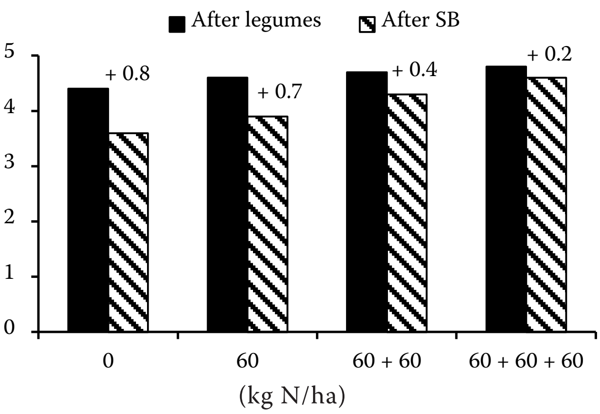

Figure 1. Differences in the seeds yield of winter rape after legume forecrops and spring barley (SB) depending on nitrogen fertilization of rape (t/ha)

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Table 4. The yield of winter wheat cultivated in the third year of rotation depending on the forecrop and nitrogen (N) fertilization (t/ha)

Forecrop (F)		N dose (kg N/ha)				Mean
		0	60	60 + 60	60 + 60 + 60	
Yellow lupin	cv. Mister	6.7	7.4	7.9	7.7	7.4^{A} (+8.8%)
	cv. Perkoz	6.7	7.6	7.8	8.0	7.5^{A} (+10.3%)
Narrow-leaved lupin	cv. Zeus	6.2	7.2	7.6	7.8	7.2^{A} (+5.9%)
	cv. Regent	6.5	7.4	7.7	7.6	7.3^{A} (+7.4)
White lupin		6.5	7.1	7.5	7.6	7.2^{A} (+5.9%)
Pea		6.2	7.1	7.5	7.5	7.1^{A} (+4.4%)
Mean for legumes		6.5	7.3	7.7	7.7	7.3 (+7.4%)
Spring barley		5.7	6.8	7.0	7.1	6.8^{B} (100%)
Mean		6.4^{c} (100%)	7.2^{b} (+12.5%)	7.6^{a} (+18.8%)	7.6^{a} (+18.8%)	7.2

Means denoted by the same letters for each factor did not differ significantly. *LSD* (least significant difference) F/N = 0.49; N/F = 0.49

cantly yield of WR cultivated after BL, PEA and SB compared to control, but between 120 kg N/ha and 180 kg N/ha, there were no significant differences. On average, forecrops increased yields of WR compared to SB: PEA and cv. BL Zeus by 0.5 t/ha, WL by 0.3 t/ha, cv. BL Regent by 0.4 t/ha and YL by 0.7 t/ha. The dose of 60 kg N/ha increased the yield of WR by about 7% and the other doses by about 12%. The most beneficial effect of legume forecrops on yields of WR was observed in the plot with no mineral N fertilization (increased by 0.8 t/ha), and the lowest when a rate of 180 kg N/ha was applied (increased by 0.2 t/ha) (Figure 1). The average grain yield of WW cultivated in the third year of rotation was 7.2 t/ha (Table 4). Independent of forecrops, each dose of nitrogen fertilization caused a significant increase of yield compared to the control. Similar to yields of WR, there was no significant increase in yields of WW cultivated in the third year of rotation when the effects of 120 kg N/ha and 180 kg N/ha doses were compared. On average, the increase of yields was remarkable after each forecrop compared to SB, the lowest after PEA (4.1%) and the highest after cv. YL Perkoz (10.3%). The dose of 60 kg N/ha increased yield by about 13% and the other doses by about 19%. The most beneficial effect of legume forecrops on yields was observed in the plot with no mineral N fertilization (increased by 0.8 t/ha), the dose of 120 kg N/ha caused an increase by 0.7 t/ha. When 60 and 180 kg N/ha doses were applied, the increase was lower (from 0.5 to 0.6 t/ha) (Figure 2a). The average grain yield of WW cultivated in the fourth year of rotation was 4.7 t/ha (Table 5). Independent of forecrop, general nitrogen fertilization caused a significant increase of yield in comparison to the control, except for the combination with cv. YL

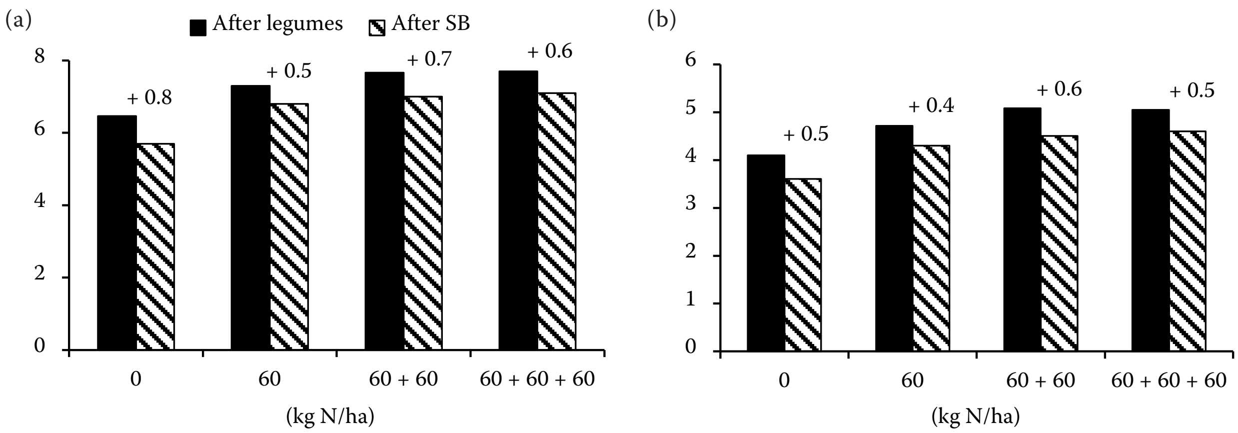

Figure 2. Differences in the grain yield of winter wheat cultivated after legume forecrops and spring barley (SB) in (a) the third year and (b) the fourth year of rotation depending on nitrogen fertilization of cereal (t/ha)

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Table 5. The yield of winter wheat cultivated in the fourth year of rotation depending on the forecrop and nitrogen (N) fertilization (t/ha)

Forecrop (F)		N dose (kg N/ha)				Mean
		0	60	60 + 60	60 + 60 + 60	
Yellow lupin	cv. Mister	4.0	4.5	5.1	4.9	4.6[A] (+7.0%)
	cv. Perkoz	4.5	4.8	5.0	5.3	4.9[A] (+14%)
Narrow-leaved lupin	cv. Zeus	4.1	4.8	5.1	5.1	4.8[A] (+11.6%)
	cv. Regent	4.0	4.7	5.1	5.0	4.7[A] (+9.3%)
White lupin		4.0	4.7	5.1	5.1	4.8[A] (+9.3%)
Pea		4.0	4.8	5.1	4.9	4.7[A] (+9.3%)
Mean for legumes		4.1	4.7	5.1	5.1	4.7 (+9.3%)
Spring barley		3.6	4.3	4.5	4.6	4.3[B] (100%)
Mean		4.0[c] (100%)	4.7[b] (+17.5%)	5.0[a] (+25.0%)	5.0[a] (+25.0%)	4.7

Means denoted by the same letters for each factor did not differ significantly. *LSD* (least significant difference) F/N = 0.52; N/F = 0.47

Perkoz, where a significant increase was only after the dose of 180 kg/ha. In other cases, 180 kg N/ha did not increase significantly yield in comparison to 120 kg N/ha. On average, the increase of yields was remarkable after each forecrop in comparison to SB. The lowest effect was after cv. YL Mister (7.0%) and the highest after cv. YL Perkoz (14%). 60 kg N/ha increased yield by 17.5% and the other doses by 25%. The beneficial effect of legume forecrops on yields ranged from 0.4 t/ha to 0.6 t/ha (Figure 2b). In comparison of yields of WW cultivated in the same years (2015–2017; the third and fourth year of rotation), it can be observed, that the lowest difference occurred when forecrop was cv. BL Zeus (0.4 t/ha) and the highest difference was 1.1 t/ha when forecrop was cv. YL Mister (Table 6). On average, the yield of WW cultivated in the fourth year of rotation was significantly lower by 0.7 t/ha (11.5%). Table 7 shows means of agronomic N-efficiency for years 2015–2017 for WW cultivated in the third and fourth year of rotation. The N-efficiency values were similar for both WW at the same range of nitrogen dose; they were getting lower when the dose was growing. However, negative efficiency occurred in the range of 120–180 kg N/ha.

Table 6. Comparison in yielding of winter wheat (WW) cultivated in the third and fourth year of rotation (mean 2015–2017) (t/ha)

Forecrop (F)		3rd year of rotation	4th year of rotation
Yellow lupin	cv. Mister	6.4	5.3
	cv. Perkoz	6.4	5.7
Narrow-leaved lupin	cv. Zeus	6.0	5.6
	cv. Regent	6.2	5.4
White lupin		6.1	5.5
Pea		6.0	5.4
Spring barley		5.5	5.0
Mean		6.1[a]	5.4[b]

Means denoted by the same letters for each factor did not differ significantly. *LSD* (least significant difference) F/WW = 0.52; WW/F = 0.30

DISCUSSION

Legumes have many benefits, but the most important is N_2 fixation. A survey of N_2 quantities fixed per unit area revealed that the principal crop legumes were ranked in the following descending order: soybean, lupin, field pea, faba bean, common bean, lentil and chickpea (Unkovich and Pate 2003). It contributes to the high-protein seeds of legumes as well as providing residues N for subsequent crops, particularly cereals and Brassica crops (Wolko et al. 2011). In our experiment, legumes increased WR yields of compared to SB as follows: PEA and cv. BL Zeus by 0.5 t/ha, WL by 0.3 t/ha, cv. BL Regent by 0.4 t/ha and YL by 0.7 t/ha. Legumes forecrops also influenced the other crops in rotation. A significant increase was noticed in yields of WW cultivated in the third and fourth year of rotation after each legume in comparison to SB. In the similar experiment of Prusiński et al. (2016), where the effect of legume forecrops and nitrogen fertilization on yielding of

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Table 7. Agronomic N-efficiency of nitrogen fertilization of winter wheat cultivated in the third and fourth year of rotation (mean 2015–2017) (kg grain/kg N)

	Nitrogen fertilization (kg N/ha)				
	0–60	0–120	0–180	60–120	120–180
3rd year of rotation	13.3	9.2	6.1	5.0	–*
4th year of rotation	11.7	9.2	6.1	6.7	–*

*negative efficiency

winter triticale was assessed, average grain yields of triticale after leguminous forecrops were statistically similar, by 0.84 t/ha higher than after spring barley. Kumar and Goh (2002) reported that significantly lower wheat grain yields obtained under non-leguminous than leguminous residues were related to lower nitrogen additions as amounts of residue-N added from ryegrass and wheat residues (64 and 72 kg N/ha, respectively) were lower than those provided by white clover and field pea residues (223 and 141 kg N/ha, respectively). When yields of WW cultivated in the same years but in a different position in the rotation were compared, it was reported that the yields of WW cultivated in the third year of rotation was significantly higher than the WW cultivated in the fourth year of rotation.

Moreover, the value of agronomic N-efficiency was similar for both WW at the same range of N doses. It means that the increase of yielding was not connected to nitrogen fertilization but to the residue of nitrogen after legume forecrops. The most beneficial effect of legume forecrops was observed on yields of WR and WW cultivated in the third year of rotation in the plot with no mineral N fertilization (increase by 0.8 t/ha). Prusiński et al. (2016) noticed in plots without mineral N fertilization by over 1.5 t/ha more grain of winter triticale after legume forecrops than in the plot after spring barley. Moreover in comparison to the control, nitrogen fertilization caused a significant increase of WR and both WW yields, but the dose of 180 kg N/ha did not increase yield significantly in comparison to 120 kg N/ha. There was also negative agronomic N-efficiency between the 120–180 kg N/ha doses, which confirms conclusion, that it is not necessary to use 180 kg N/ha, especially if there are legumes in crop rotation. However, newer cultivars can react differently to such fertilizer rates. In the study of Schuster and Rathke (2001) optimum N-fertilization dose amounted to 150 kg N/ha for conventional varieties as well as for transgenic hybrids of winter oilseed rape. In another experiment, Rathke and Schuster (2001) observed increased yields of winter rape at doses of 80–160 kg N/ha, whereas there was only a small rise in yields from 160 to 240 kg N/ha. These results were confirmed in another experiment (Rathke et al. 2005). The impact of nitrogen fertilization on the seed yield of winter wheat has been described in many studies. For example, the study of Ruža et al. (2012) on the effect of N-fertilization rate showed that the grain yield of winter wheat increased until the rate of 120–150 kg N/ha, but the grain quality increased until the rate of 180 kg N/ha. Litke et al. (2017) showed that grain yield of winter wheat significantly increased until the nitrogen fertilizer rate of 180 kg N/ha after both forecrops (winter wheat and winter rape). For economic and ecological reasons, excessive fertilizer N-input to cropping systems is critical. Therefore, nitrogen fertilization should meet the actual N demands of the plant (Rathke et al. 2006). According to Piekarczyk (2010) winter wheat grain yield and its quality on a worse stand cannot be improved by increased fertilization. In his study, the most favourable stand for winter wheat yield was narrow-leaved lupin in pure sowing. Spring rape and also a mixture of lupin with spring triticale and spring barley were worse forecrops than narrow-leaved lupine. On light soil in regions and years with relatively low precipitation sums during the growth period, independently of forecrop, nitrogen fertilization above 80 kg N/ha did not increase significantly grain yield but affected positively its technological quality.

The present study showed that legumes as forecrops increased yield of all after-harvest crops in rotation: winter rape-winter wheat-winter wheat. The dose of 180 kg N/ha did not increase significantly yield of cereals and WR in comparison to 120 kg N/ha. There was also negative agronomic N-efficiency between doses of 120–180 kg N/ha, which means that it is not necessary to use 180 kg N/ha, especially if there are legumes in crop rotation.

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