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ORIGINAL RESEARCH PAPER

Biological and production responses of intercropped plants of pea, spring wheat, and linseed

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Abstract

Given the growing interest in ecological intensification directed towards sustainable crop production, a study was conducted to assess the biological and production response of pea intercropped with spring wheat or linseed under various growing conditions. The experiment was conducted in 2009–2011 on a Haplic Phaeozem soil in the western part of Poland. Intercropping of pea significantly reduced the green area index and the normalized difference vegetation index values, but growing pea with linseed caused a significant increase in the number of nodes with pods, pods per stem, and seeds per stem. Intercropping with wheat increased the seed number per pod. Seed inoculation with Nitragina significantly increased the number of pea pods and seeds per stem. Wheat intercropped with pea, with inoculation and foliar fertilization, attained significantly lower straw weight and spike length. Intercropping of linseed significantly reduced the features of the yield structure. Bacterial inoculation increased the production potential of pea at the expense of the supporting plants.

Keywords

Pisum sativum L.; plant interaction; *Rhizobium* inoculation

Introduction

Interest in sustainable agriculture, which assumes increased diversification of crop rotations, biodiversity and promotion of legumes, continues to grow around the world [1,2]. Cultivation of legumes, alone or in mixed croppings with other plants, has an important role in sustainable development policy. In Europe, mixtures of cereals or cereals with legumes are dominant [3,4], but in recent years there has been increasing interest in mixtures of legumes and linseed [5,6]. Cereal–legume mixtures in Europe are harvested for green matter and seeds as a valuable source of fodder protein and for soil nitrogen enhancement for crops [7–9]. The popularity of intercropping is mainly due to its higher yield potential in comparison to sole cropping, whilst the weighted average of components is similar to that of the better species [10]. Trends in global agriculture are heading towards increasing the productivity of biologically diverse plants. In many regions of the world pea is the leading leguminous plant, represented by general purpose or fodder cultivars. The cultivation of peas in mixtures, currently mainly with spring cereals, makes it possible to increase the yield of above-ground biomass per unit area [11]. Intercropping of cereals with pea is an effective solution for sustainable agriculture, as it increases nitrogen yield per unit area and reduces leaching of nitrogen compounds from the soil profile by rain and groundwater [7,12]. The yield of mixtures of spring cereals with legumes depends on many factors, of which the most important are the selection of component species and their share in the mixture, as well as the prevailing weather conditions [13,14]. If the species present in the mixture do not differ in their morphological characteristics, then the requirements of each component for water, nutrients and light increases interspecies competition [15]. A fundamental problem in cereal–legume mixtures is the poor ability of legumes to compete with the dominant cereal crop, which determines how much of each component is sown [16]. The literature on intercropping mixtures is extensive, but most of these studies focus on evaluation of the final effect, i.e., the seed yield, whereas few concern overall productivity, including biomass. It is therefore necessary to develop this issue by undertaking alternative research to verify the productivity of linseed with pea in comparison to wheat and pea.

Cultivation of linseed in two-species mixtures can be expected to become an effective agrotechnical option in comparison to sole cropping. In addition, we expect that by applying micronutrient fertilizers and inoculating the soil with bacteria of the genus *Rhizobium* before sowing we can improve the yield efficiency of pea and reduce its aggressiveness in the mixture. The current literature also lacks information on biometric features and growth indicators of pea intercropped with linseed or spring wheat. The aim of this study was therefore to assess the physiological parameters and morphological characteristics of the afila pea intercropped with spring wheat or linseed in varied habitat conditions.

Material and methods

Study area and experimental design

A field experiment was carried out in the years 2009–2011 at the Bayer Polska Experimental Station in the village of Modzurów (50°09′ N, 18°07′ E). The soil of the experiment was a Haplic Phaeozem (WRB 2015) characterized by pH 6.3 and 19.1, 21.7, and 10.1 mg of available phosphorus, potassium, and magnesium, respectively, per 100 g soil in the top soil layer. The content of total mineral nitrogen in the soil (at a 0–90 cm depth) was 73.6–77.3 kg ha^{-1}, and the C:N ratio was in the range of 9.0–9.5. NPK fertilizer in the form of Polifoska (8–24–24) and 57% potash was applied before sowing at the rate of 20 N, 48 P, and 72 K kg ha^{-1}.

The precrop was winter wheat in all 3 years. Linseed was fertilized with 60 kg ha^{-1} N and the mixtures of linseed and pea with 40 kg ha^{-1} N. The spring wheat grown alone was fertilized with 120 kg ha^{-1} N due to the unsuitable winter wheat precrop, whereas the wheat and pea mixtures were fertilized with nitrogen in the same amount as the mixtures of linseed and pea. Nitrogen was applied a second time to the linseed and pea mixture as a top dressing at the "herringbone" stage of linseed and at the onset of stem elongation for wheat. Fertilization of pea was performed with to 20 kg N ha^{-1}, 48 kg P ha^{-1}, and 72 ha^{-1} K in form of Polifoska (8% N, 24% P, 24% K) and potassium chloride (57% K). Intercrops of pea with linseed or wheat were fertilized with 40 kg ha^{-1} N. The seeds of the mixtures were sown twice in order to place them in the soil properly, as pea was sown at a depth of 6 cm, wheat 3 cm, and linseed 2 cm. In the sole cropping, germinating seeds were sown at the rate of (total number of seeds per m^2) 120 for pea and 480 for wheat and linseed. The sowing rate was halved in the mixtures. Pea was sown first and then the other species, according to the sowing schedule. The area of the plots for harvest ranged from 8.4 to 12 m^2 in the years of the study, and the row spacing for peas was 15 cm. Each plot had seven rows. All pea seeds were dressed with the fungicide Tiuram 1 day before sowing. Immediately after sowing of pea in the sole cropping, a mixture of Chlomazon (0.2 dm^3 ha^{-1}) and Linuron (1.0 dm^3 ha^{-1}) was applied. Weeds were controlled in the mixtures of pea with spring wheat and linseed using Bentazon at 2.8 dm^3 ha^{-1}.

A two-factor field experiment was set up in a spilt-plot design with treatment as the main plot factor and crop stand as the subplot factor. The treatments included: *Rhizobium leguminosarum* inoculation (Nitragina), foliar fertilization (Photrel), and a combination of Nitargina + Photrel. Inoculation of pea seeds with *Rhizobium* inoculants Nitragina was performed 1 day before sowing. Foliar fertilizer Photrel (150 g ha^{-1} of B, 210 g ha^{-1} of Mn, 12 g ha^{-1} of Mo, 400 g ha^{-1} of MgO, and 1,081 g ha^{-1} of SO_3) was applied at the beginning of the plant budding stage (BBCH 51) was applied at the rate of 3 dm^3 ha^{-1}. The factor crop stand included: pure pea and intercrops of pea/linseed and pea/wheat. Pure stands of pea (*Pisum sativum* L. 'Tarchalska'), wheat (*Triticum aestivum* L. 'Koksa'), and linseed (*Linum usitatissimum* L. 'Szafir') were established with 120 (pea) and 480 (wheat and linseed) germinable seeds m^{-2}. For intercrops, half of the sowing density of the pure stands was used for both partners. Intercrops were sown individually with an Oyord plot drill due to the different sowing depth requirements of the crops. Three replications were performed. The plot size was 10 m^2. Sowing depths were: for pea 6 cm, wheat 3 cm, and linseed 2 cm, and the row spacing 15 cm. Pea was sown first. Sowing was conducted in early April in each year. All harvests were performed mechanically in early August each year.

Physiological analysis

The following vegetation indices: GAI, NDVI, SPAD, stomatal resistance, and stomatal conductance were measured at the characteristic stages of pea plant development; Stage 1 – inflorescence emergence (BBCH 51–57), 2 – onset of flowering (BBCH 62–64), 3 – end of flowering (BBCH 67–69), and 4 – end of fruit development (BBCH 77–79). The green area index (GAI) of the pea canopy was measured with a Delta-T Sunscan System (Delta-T Devices Ltd, UK), the normalized difference vegetation index (NDVI) with a GreenSeeker unit (N-tech, USA), plant analysis development (SPAD) with a Minolta SPAD 502DL chlorophyll meter, stomatal resistance with a Delta-T AP4 porometer (Delta-T Devices Ltd), and stomatal conductance with a LCi-SD Ultra Compact Photosynthesis System (ADC BioScientific Ltd, UK).

The NDVI value is calculated from reflectance measurements in the red and near infrared (NIR) portion of the spectrum: $NDVI = R_{\mathrm{NIR}} - R_{\mathrm{Red}} / R_{\mathrm{NIR}} + R_{\mathrm{Red}}$, where R_{NIR} is the reflectance of NIR radiation and R_{Red} is the reflectance of visible red radiation. The NDVI values range from −1 to 1, so that the vegetation is greener as the value approaches 1. The green area index (GAI) measurements were taken for all plots in the experiment using the Delta-T Sunscan System. All measurements such as GAI, NDVI, SPAD, stomatal resistance, and stomatal conductance were made three times at each of four growth stages.

Biometric analysis

The generative shoot density (per m^2) of pea and of spring wheat and linseed were calculated at the flowering stage (BBCH 67–69) of pea, followed by biometric analysis of 30 plants per plot. The following pea characteristics were then analyzed: stem length to the first pod, length of the part of the stem with pods, total stem length, number of nodes with pods per shoot, number of pods per shoot, number of seeds per pod, total number of seeds per stem, weight of single seed, seed weight per stem, weight of vegetative parts of generative shoot, and total stem weight. The harvest index was also calculated.

Thirty culms/shoots from each plot were randomly selected for biometric analysis at the senescence stage of wheat (BBCH 93) and yellow maturity of linseed (BBCH 83). The following biometric measurements were made for a single culm of spring wheat: culm length, spike length, number of spikelets per spike, number of grains per spike, weight of grains from one spike, 1,000-grain weight, and straw weight. Based on the known weight of the grain and straw, the stem weight was estimated and the harvest index for the plant was calculated. The following biometric measurements were made for linseed: stem length to the first branch, stem length with branches, stem height, number of branches per stem, number of capsules per stem, and total number of seeds. The number of seeds and capsules per stem were used to calculate the average number of seeds per capsule, 1,000-seed weight and seed yield per plant (stem). The total biomass yield of the plant (seeds + straw) was estimated and the harvest index was calculated.

Tab. 1 Selected growth stages of pea during the 3 years of study.

Growth stages	2009	2010	2011
Inflorescence emergence (BBCH 51–57)	May 23	May 21	May 12
Inflorescence emergence (BBCH 51–57)	May 30	May 29	May 20
End of flowering (BBCH 67–69)	Jun. 15	Jun. 13	Jun. 6
End of fruit development (BBCH 77–79)	Aug. 4	Jul. 28	Jul. 28

Weather conditions

Weather conditions are presented in Tab. 1. In 2009, they were variable due to heavy rainfall in March (96.6 mm). In May, it was warm (55 mm and 14°C), whereas in June (109.2 mm and 15.9°C) and July (137 mm and 20°C) it was relatively humid. Year 2010 was the most humid year of all in the investigated 3-year period mainly due to abundant precipitation in May and July (193 and 208 mm, respectively). In the following year, 2011, a lower amount of precipitation was recorded over the whole vegetative period. Only in July was it relatively wet (168 mm).

Statistical analysis

All data were statistically analyzed by analysis of variance using Statistica 10.0 software (Stat Soft Inc., USA). Significant differences (HSD) were verified using Tukey's test at the significant level of $p < 0.05$.

Results

Pea vegetation indices at characteristic developmental stages depend on the cropping system

The GAI of the afila pea crop grown alone was significantly higher than in the case of intercropping of this species with spring wheat or linseed (Tab. 2). These results were determined by the lower biomass of the supporting species in the two-species mixtures with pea.

Foliar application of the micronutrient fertilizer Photrel significantly increased the GAI of the crop at the end of fruit development (BBCH 77–79), on average by 0.55 m^2 m^{-2} compared to the control, probably by extending the life-span of the leaves. The chemical factor (foliar fertilization) did not significantly influence NDVI values. However, significantly higher NDVI values in BBCH 51–57 (0.524) and BBCH 67–69 (0.634) were noted for the pea crop grown alone. The gas exchange indices for pea, i.e., stomatal resistance and conductance, varied considerably at different stages of the crop development. The stomatal resistance of the pea plants ranged from 1.54 to 5.42 s cm^{-1}, and stomatal conductance from 0.30 to 0.90 cm s^{-1}. Significantly lower stomatal resistances were observed at the inflorescence emergence stage of pea (BBCH 51–57), intercropped with wheat or linseed (3.08 and 3.25 s cm^{-1}, respectively) than for sole cropping of pea. The reverse was observed for stomatal conductance, which was significantly lower for pea plants grown alone than in the intercropping plots during the flowering period. Foliar fertilization with Photrel significantly affected stomatal conductance at inflorescence emergence stage (BBCH 51–57), and the directions of this effect were different. Photrel significantly decreased this parameter (0.32 cm s^{-1}), whereas bacterial inoculation with Nitragina significantly increased it (0.51 cm s^{-1}) as compared to the control (Tab. 2).

Morphological characteristics of pea stems depend on the cropping system and on presowing seed inoculation and foliar application of a micronutrient fertilizer

The first pod of the afila pea plants grown alone formed slightly lower (at 59.5 cm) than in the pea plants intercropped with wheat or linseed (Tab. 3). As a consequence, under the conditions of intercropping of pea with spring wheat, the fruiting part of the pea stem was significantly shorter, which should be considered an unfavorable situation. The effect of these changes was to reduce the height of the pea plants grown with wheat.

Tab. 2 Comparison of vegetation indices for the afila pea crop in characteristic developmental stages for different ways of sowing and on presowing seed inoculation and foliar application of a micronutrient fertilizer (mean from three growing seasons).

Vegetation index	Stage*	Sowing way**				Treatment***				
		P	M1	M2	$LSD_{0.05}$	Control	Ni.	Ph.	Ni.+Ph.	$LSD_{0.05}$
GAI ($m^2\ m^{-2}$)	1	2.55	1.77	1.65	0.445	2.20	2.24	2.04	2.03	NS
	2	3.65	3.37	2.80	0.298	3.29	3.31	3.15	3.34	NS
	3	4.12	3.96	3.70	NS	3.98	4.02	3.92	3.92	NS
	4	3.58	2.79	3.03	0.289	3.08	3.09	3.64	3.35	0.325
NDVI	1	0.524	0.442	0.394	0.096	0.476	0.462	0.461	0.462	NS
	2	0.542	0.534	0.509	NS	0.492	0.546	0.550	0.525	NS
	3	0.634	0.578	0.593	0.036	0.595	0.607	0.606	0.609	NS
	4	0.420	0.379	0.353	NS	0.387	0.383	0.397	0.384	NS
SPAD	1	37.2	37.8	37.1	NS	37.0	37.5	38.1	36.7	NS
	2	42.4	43.2	42.9	NS	42.8	43.9	42.7	42.1	NS
	3	46.9	47.6	47.3	NS	47.1	47.0	47.4	47.7	NS
	4	27.4	29.1	28.6	NS	27.6	29.1	28.5	28.2	NS
Stomatal resistance ($s\ cm^{-1}$)	1	5.42	3.08	3.25	1.821	5.05	2.73	4.73	3.14	NS
	2	1.57	1.54	2.04	0.421	1.83	2.00	1.34	1.69	NS
	3	2.61	1.68	2.12	0.620	2.30	2.02	1.99	2.23	NS
Stomatal conductance ($cm\ s^{-1}$)	1	0.301	0.475	0.501	0.109	0.441	0.505	0.318	0.453	0.127
	2	0.856	0.902	0.887	NS	0.826	0.906	0.944	0.851	NS
	3	0.704	0.890	0.732	0.158	0.861	0.689	0.780	0.770	NS

* Stages: 1 – inflorescence emergence (BBCH 51–57); 2 – onset of flowering (BBCH 62–64); 3 – end of flowering (BBCH 67–69); 4 – end of fruit development (BBCH 77–79). ** Cropping system: P – sole cropping of pea 100%; M1 – intercropping of pea 50% with spring wheat 50%; M2 – intercropping of pea 50% with linseed 50%. *** Treatment: Ni. – Nitragina; Ph. – Photrel. NS – not significant.

Tab. 3 Comparison of morphological characteristics of pea stems depending on the manner of sowing and on presowing seed inoculation and foliar application of a micronutrient fertilizer (mean from three growing seasons).

Feature*	Unit	Sowing way**				Treatment***				
		P	M1	M2	$LSD_{0.05}$	Control	Ni.	Ph.	Ni.+Ph.	$LSD_{0.05}$
1	cm	59.5	61.2	60.7	NS	61.3	57.9	60.9	61.7	3.13
2	cm	20.9	15.5	20.7	2.25	16.7	20.1	19.3	20.1	2.86
3	cm	80.5	76.7	81.4	2.92	78.0	78.1	80.3	81.7	3.71
4	-	3.70	3.76	4.65	0.47	3.54	4.39	4.09	4.13	0.60
5	-	6.48	5.65	6.80	0.660	5.62	6.80	6.30	6.52	0.838
6	-	4.06	4.26	4.19	NS	4.10	4.05	4.38	4.15	NS
7	-	26.4	23.9	28.0	3.03	23.0	27.7	27.0	26.7	3.85
8	mg	270.9	266.6	276.8	NS	279.3	265.6	274.2	266.6	13.65
9	g	7.16	6.37	7.72	0.831	6.43	7.29	7.44	7.15	NS
10	g	4.13	4.14	5.24	0.461	4.24	4.53	4.70	4.55	NS
11	g	11.29	10.51	12.97	1.216	10.67	11.82	12.14	11.70	NS
12	$g\ g^{-1}$	0.622	0.594	0.588	0.0221	0.591	0.611	0.599	0.605	NS
13	1–9	3.2	5.1	4.3	0.82	4.1	4.3	4.2	4.2	NS

* Features: 1 – stem length to first pod; 2 – length of part of stem with pods; 3 – stem height; 4 – number of nodes with pods per stem; 5 – number of pods per stem; 6 – number of seeds per pod; 7 – number of seeds per stem; 8 – weight of single seed; 9 – seed weight per stem; 10 – weight of vegetative parts of stem; 11 – total stem weight; 12 – harvest index; 13 – lodging, on a scale of 1 to 9, where 1 is 100% lodging and 9 is no lodging. ** Cropping system: Tab. 2. *** Treatment: see Tab. 2. NS – not significant.

Intercropping of pea with linseed significantly increased the number of nodes on the fruiting part of the stem (4.65) relative to the control (3.70). The number of nodes with pods on the pea stems increased (4.39) significantly after bacterial inoculation. Changes in the length of the fruiting part of the pea plants, followed by changes in the number of nodes with pods, led to significant changes in the number of fruits and seeds. The greatest number of pods (6.8) was formed by pea plants intercropped with linseed. Similar production potential in terms of the number of fruits per plant was obtained for peas following bacterial inoculation. The cropping system for pea – alone or mixed – and inoculation with rhizobia or foliar application of micronutrient fertilizer, did not significantly affect the number of seeds per pod. The seed weight per stem was significantly affected by the cropping system employed. A significant increase in the seed weight per stem was observed in the mixture of pea and linseed (7.72 g), and a significant reduction, relative to this mixture with the pea–wheat mixture (6.37 g). This response of pea in its development and production indicates that agrobiological methods can be used to control the productivity of this species, albeit to a small extent. The most massive stalks were formed by the afila pea plants intercropped with linseed (12.97 g). The high productivity of these pea plants intercropped with linseed resulted in a significantly lower harvest index (0.59).

Morphological characteristics of wheat depend on the cropping system and on presowing seed inoculation and foliar application of a micronutrient fertilizer

Sowing spring wheat in a mixture with afila pea led to a decrease in the culm length of wheat (72.1 cm) compared to this mixed cultivation with fertilization (77.4 cm) (Tab. 4). The application of Photrel increased the length of the wheat spike (8.44 cm) compared to treatments which included Nitragina application (B and D). Improvement of the developmental conditions for pea plants by inoculating the seeds with rhizobia and by foliar application of the micronutrient fertilizer led to a decrease in spike length (7.58 cm) and subsequently in the number of spikelets (15.1) and grains per spike (28.4), especially in Treatment D. This response of wheat resulted in a decrease in grain and straw production at the level of the individual plant and of the canopy. Foliar application of the microelement fertilizer (Treatments C and D) significantly decreased the harvest index of spring wheat (0.45 and 0.46, respectively) due to the increased height of the pea plants which raised the level of competition in the pea–wheat mixtures.

Tab. 4 Morphological characteristics of spring wheat plants sown in mixtures with pea (Treatments A–D) and in sole cropping (Treatment E) (mean from three growing seasons).

	Stem and spike features								
	Length (cm)		Number		Weight (g)				
Treatment*	Culm	Spike	Spikelets	Grains	Grains per spike	1,000 grains	Straw	Plant	Harvest index
A	72.1	8.37	16.8	32.6	1.28	39.1	1.29	2.58	0.490
B	73.3	7.97	16.3	32.2	1.25	38.6	1.26	2.51	0.493
C	77.4	8.44	16.6	31.4	1.30	40.2	1.49	2.79	0.452
D	72.3	7.58	15.1	28.4	1.06	37.3	1.20	2.26	0.461
E	75.0	7.87	16.6	34.1	1.36	39.8	1.40	2.76	0.489
$LSD_{0.05}$	4.12	0.635	1.14	5.19	0.241	NS	0.195	0.407	0.0357

* Treatments: A – mixture of pea 50% with spring wheat 50%; B – mixture of pea 50% inoculated with Nitragina with spring wheat 50%; C – mixture of pea 50% with spring wheat 50% and application of Photrel fertilizer; D – mixture of pea 50% with spring wheat 50%, application of Nitragina and Photrel as in Treatment C; E – sole cropping of spring wheat 100%. NS – not significant.

Morphological characteristics of linseed depend on the method of sowing and on presowing seed inoculation and foliar application of micronutrient fertilizer

Intercropping of linseed as a supporting plant with afila pea led to a slight decrease in the height of the plants (Tab. 5). The shortening of the upper part of the stem from which branches grew significantly reduced the number of branches in all intercropping treatments. This clearly points to interspecies competition between the afila pea and linseed when grown together. The interlocking of the plants of the two-species mixture, due to the strong tendrils of 'Tarchalska' of afila pea could be expected to mechanically impede the initiation and development of linseed branches. The reduced number of branches on the linseed stem at the same time reduced the number of seed capsules, and consequently the number of seeds. As expected, this response of the linseed plants resulted in a decrease in the weight of seeds per stem and thus in the harvest index of linseed in the intercropping treatments.

Tab. 5 Morphological characteristics of linseed sown in mixtures with pea (Treatments A–D) and in sole cropping (Treatment E) (mean from three growing seasons).

	Morphological and production features of linseed stem**										
	Length (cm)			Number				Weight (g)			Harvest index (g g^{-1})
Treatment*	1	2	3	4	5	6	7	8	9	10	
A	44.8	18.8	63.6	4.57	9.40	60.7	6.88	7.87	0.495	0.766	0.370
B	46.9	17.1	64.0	4.39	10.12	66.0	6.52	8.06	0.532	0.767	0.409
C	43.9	19.2	61.9	4.71	10.00	63.5	6.59	7.45	0.518	0.728	0.382
D	46.5	18.2	64.7	4.72	10.90	75.9	6.87	7.94	0.596	0.823	0.396
E	48.4	19.1	67.5	6.67	13.80	95.1	7.05	7.62	0.739	1.040	0.412
$LSD_{0.05}$	NS	NS	NS	0.845	2.32	12.6	NS	NS	0.075	0.102	NS

* Treatments: A – mixture of pea 50% with linseed 50%; B – mixture of pea 50% inoculated with Nitragina with linseed 50%; C – mixture of pea 50% with linseed and application of Photrel fertilizer; D – mixture of pea 50% with linseed 50%, Nitragina application as in Treatment B and Photrel as in Treatment C; E – sole cropping of linseed 100%. ** Morphological and production features of linseed stem: 1 – stem length to first branch; 2 – stem length with branches; 3 – stem height; 4 – number of branches per stem; 5 – number of capsules per stem; 6 – number of seeds; 7 – number of seeds per capsule; 8 – 1,000-seed weight; 9 – seed yield per plant; 10 – biomass yield (seeds + straw). NS – not significant.

Discussion

Our study has shown that the production potential of afila pea varied depending on the manner of sowing. The imperative for this agronomic solution is to try to simultaneously produce two raw materials with diametrically different purposes. Determinants of the productivity of the pea stem induced by the sowing method, analyzed at the level of the plant were generally significant, but the vegetation indices did not differ. During each of the characteristic stages of pea ontogenesis, a larger GAI was obtained in the pea crop grown alone. At the end of the flowering stage, the GAI for pea grown in a pure stand and in mixtures with spring wheat or linseed were 4.12, 3.96, and 3.7 m^2 m^{-2}, respectively. During the ripening stage, when flat green pods were formed, the GAI decreased as expected. The values were 3.58 for pea under sole cropping, and significantly lower in the mixtures with wheat or linseed, 2.79 and 3.03 m^2 m^{-2}, respectively. An earlier study by Dhar et al. [17] supports these results, indicating that peas grown alone attain higher LAI values throughout the development period in comparison to intercropped peas. In our study the GAI values were highest in the flowering stage and then decreased with a decrease in foliar mass. Similar results were observed by Klimek-Kopyra et al. [18].

Our study has shown that intercropping of pea had a negative effect on the NDVI values at inflorescence emergence (BBCH 51–57) and at the end of flowering (BBCH 67–69). Different results were obtained by Trail et al. [9], indicating that the NDVI may be determined by the presence of a component species. These authors showed that an increase in NDVI of 18% for mulched millet and up to 16% for intercropped millet as compared to a crop of millet alone. In our study, an increase in the biological condition of the soil through inoculation with the bacterial product Nitragina only slightly increased the NDVI, but resulted in a significant increase in the stomatal conductance of the pea leaves.

Analysis of the responses of the plants to intercropping revealed that the mixture had a one-sided benefit. Pea intercropped with linseed significantly increased its productivity through an increase in the number of pods and seeds and the seed weight, at the expense of linseed. The shortening of the upper part of the linseed stem from which the branches grow, resulted in a significant reduction in the number of branches in all treatments with all intercropping treatments with linseed. This clearly indicates interspecies competition between the afila pea and linseed when grown together. These results are confirmed by those of Zając et al. [19] who showed that linseed is dominant in a mixture with pea. These authors showed that mutual aggressiveness between linseed and pea when grown together was higher in years with less favorable weather conditions, when the development of one species was overly favoured. The seed yield from a single linseed plant showed a highly significant interaction with the growing season and a weaker interaction with the cropping method – sole cropping or intercropping with pea. Similar interdependencies in a canopy of linseed and pea mixtures were found for the competitiveness index (CR), which was higher for a mixture of 'Flanders' linseed and the edible cultivar 'Ramrod' of pea than in a mixture of 'Barbara' linseed and the 'Phonix' fodder cultivar of pea [19]. More complex results were presented by Klimek-Kopyra et al. [20], since they indicated that linseed appeared to be a competitor to pea during the vegetative phase. The negative impact of linseed in a mixed crop is reflected by the cooperation–competition model parameter (ICCF −0.0276) and is reflected in the lower pea biomass achievement in comparison to a sole crop. Similar observations about species competition were reported by Klimek-Kopyra et al. [21] who compared the productivity of linseed intercropped with wheat. The productivity of plants with intercropping was about 28% lower than when in sole cropping. The reaction of wheat to intercropping with pea in our study was different. Wheat in intercropping plots showed an increase in spike length and the number of spikelets per spike only, as a result of foliar fertilization of the canopy. However, improving the quality of the soil for pea through bacterial inoculation before sowing resulted in a decrease in the production potential of wheat. In the case of linseed grown with intercropping, this bacterial inoculation significantly increased the weight of the seeds. These results indicate that ecological intensification applied to peas in mixed cropping systems in order to increase nitrogen fixation has different effects on the component species – a negative effect on the grain component and a positive one for the oilseed component.

Conclusions

Pea responded negatively to the presence of the component species when intercropped during its growth and development, with a significant reduction in the GAI and NDVI. The production potential of a single pea stem in sole cropping conditions was lower than when intercropping with linseed, but higher than in the mixture with spring wheat. The production potential of wheat was shown to be determined by the cropping system. Intercropping of wheat, together with soil inoculation with rhizobia and application of a foliar fertilizer, reduced the number of grains per spike, the number of spikelets per spike, and spike length. Bacterial inoculation when intercropping peas with linseed or wheat increased pea productivity at the expense of the supporting plants.

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Biologiczno-produkcyjna reakcja grochu, pszenicy i lnu uprawianych w siewie mieszanym

Streszczenie

W ostatnich latach obserwuje się istotny wzrost zainteresowania koncepcją intensyfikacji ekologicznej ukierunkowaną na bioróżnorodność pól uprawnych. Dlatego celem pracy była ocena reakcji biologiczno-produkcyjnej grochu uprawianego w siewie mieszanym z pszenicą jarą lub lnem oleistym, w różnych warunkach siedliska. Doświadczenie wykonano w latach 2009–2011 na glebie czarnoziemnej w Stacji Doświadczalnej w Modzurowie (Polska). W badaniach wykazano, że siew mieszany grochu istotnie zmniejszył wartości GAI (*green area index* – wskaźnik zielonej powierzchni asymilacyjnej), NDVI (*normalized difference vegetation index* – znormalizowany wskaźnik wegetacji). Jednakże uprawa grochu w siewie mieszanym z lnem skutkowała istotnym wzrostem ilości wykształconych węzłów ze strąkami, liczby strąków na pędzie, liczby nasion z pędu, a w mieszance z pszenicą wzrost liczby nasion w strąku. Szczepienie nasion Nitraginą istotnie zwiększyło liczbę strąków na pędzie oraz liczbę nasion z pędu grochu. Pszenica w siewie mieszanym z grochem, przy uwzględnieniu nawożenia nalistnego i szczepienia, uzyskała istotnie niższą masę słomy oraz długość kłosa. Uprawa lnu w siewie mieszanym skutkowała istotnym zmniejszeniem cech struktury plonu. Szczepionka bakteryjna zwiększa potencjał produkcyjny grochu kosztem rośliny podporowej.