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## ORIGINAL RESEARCH PAPER

# Biodiversity of weed communities in common wheat and spelt following various forecrops

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**Abstract**

Environmentally-friendly solutions are increasingly often applied in crop cultivation technologies. These include, among others, the return of old crops (e.g., spelt wheat) and crop rotation. Ensuring a proper forecrop is essential, especially in the cultivation of winter wheat, which is susceptible to infestation by weeds. However, there is only sparse information on infestation by weeds in the cultivation of winter spelt. In this study, it was assumed that this crop is invaded by weeds to a lesser extent than wheat, especially after unfavorable forecrops. The study was based on a field experiment conducted in the east part of Poland. The aim was to compare the weed infestation of common wheat and spelt wheat grown after peas, oilseed rape, and after itself. Analyses of weed infestation were conducted in 2014–2016. The weed species composition and population size were determined as well as their dry weight. The following indices were calculated: index of species richness, Simpson's domination index, Shannon–Wiener index of species diversity, and Pielou's index of evenness. The weed infestation of spelt wheat was higher than that of common wheat during the tillering stage. It was similar in both species during the heading stage. The lowest weed infestation in both cereals was observed on a field where peas had grown. Growing after oilseed rape and after themselves contributed to an increase in weed infestation. Biomass of weeds in a field of spelt was similar after all forecrops, unlike that in wheat, where more biomass was observed after oilseed rape and wheat. A greater share of *Apera spica-venti* and *Viola arvensis* was observed in common wheat and spelt grown after oilseed rape and after themselves. Weed communities in spelt were more diverse than in wheat. The forecrops did not differentiate the species diversity in either crop.

**Keywords**

number and dry matter of weeds; species composition of weeds; growth stages; diversity indices

**Introduction**

Sustainable crop cultivation involves the use of such agrotechnological solutions which will ensure obtaining a high good quality yield and which will improve (or preserve) the properties of the agroecosystem without disrupting its function. Crop rotation is one of the elements of agrotechnology which is environmentally friendly [1]. A properly planned crop sequence allows the control of weed infestation at a level which does not threaten the yield and, in consequence, reduces the amount of chemical pesticides used [2–4]. It increases the biodiversity of an agroecosystem and, in consequence, its stability [5]. However, this factor is not widely appreciated and therefore rarely applied in practice.

The crop sequence of the various morphologies of above-ground parts and roots, the developmental cycle, nutritional needs, and strength of competition against weeds for environmental resources and by allelopathy are all factors which disrupt the continuity of the occurrence of weeds in a field in successive years and restrict their density and development. Ensuring the correct plant sequence is of particular importance for winter wheat which is susceptible to weed pressure. Its cultivation after adverse forecrops, especially after wheat and other cereals, increases the population size and biomass of weeds in communities, whilst reducing their species composition and causing one or several species of a great competitive strength against the crop to dominate [1,6]. Although the literature on the effect of forecrops on weed infestation in common wheat is relatively extensive, there is a scarcity of information about spelt – a wheat subspecies which is increasingly grown due to its nutritional values. This plant, as a primitive subspecies of wheat, is less ennobled and differs from common wheat by a number of features, both morphological and in its chemical composition and environmental requirements. Spelt is more tolerant to cultivation in conditions less favorable for growing wheat (in terms of soil quality and climate); it is more resistant to diseases and its cultivation has a beneficial effect on biodiversity [7–9]. This crop is believed to succumb to weed pressure to a lesser extent than common wheat.

This study was established to verify the hypotheses that: (i) spelt will compete against weeds more effectively than common wheat, (ii) communities of weeds in spelt grown after the forecrops under study will differ less between each other in terms of population sizes and biomass and will be more biodiverse than communities in common wheat. These hypotheses were tested in a study to assess the weed communities in winter wheat and winter spelt, grown after peas, winter oilseed rape, spring barley, and after winter wheat (common/spelt).

## Material and methods

### Site and set-up of the trial

The trial was conducted from fall 2011 in a strict, static, two-factorial field design at the research site of the University of Warmia and Mazury in Olsztyn (53°35'46" N, 19°51'18" E) (Poland).

Design factors:

- Subspecies of winter wheat: common wheat and spelt;
- Growing common wheat and spelt after peas, winter oilseed rape, and after winter common wheat / spelt.

‘Muszelka’ was the cultivar of common wheat tested and ‘Rokosz’ that of spelt.

The trial was conducted over three wheat growing seasons: 1: 2013/2014, 2: 2014/2015, and 3: 2015/2016, representing the third, fourth, and fifth years of the trial. It was designed with random blocks with four replications. Weed infestation was followed on 24 plots in which common wheat and spelt were sown. The soil on all plots was a silty fine clay, typical grey-brown podsol. It was slightly acidic, containing 8.6 to 9.3 g kg<sup>-1</sup> of organic carbon, a medium-to-high concentration of phosphorus and potassium, and a low concentration of magnesium.

Soil tillage for wheat and spelt cultivation involved ploughing and treatment with a cultivation unit and a harrow. Nitrogen fertilization (in the form of ammonium nitrate NH<sub>4</sub>NO<sub>3</sub> 34%) was applied at 160 kg ha<sup>-1</sup> for common wheat and spelt wheat on plots after oilseed rape, common wheat, and spelt wheat and 140 kg ha<sup>-1</sup> on plots after peas. Doses of phosphorus (in the form of superphosphate 40% P<sub>2</sub>O<sub>5</sub>) and potassium (potassium salt 60% K<sub>2</sub>O) were not varied depending on the forecrops and were 32.5 kg ha<sup>-1</sup> and 91.3 kg ha<sup>-1</sup>, respectively. Wheat and spelt were sown on the optimum agrotechnical dates (2013 – 21.09, 2014 – 18.09, 2015 – 12.09.) at a density of 450 m<sup>-2</sup> germinating grains. ‘Mustang’ (florasulam 6.25 g L<sup>-1</sup> + 2.4 D 300 g L<sup>-1</sup>) was applied at the rate of 0.7 dm<sup>3</sup> ha<sup>-1</sup> at the tillering stage to reduce the number of weeds.

## Weather conditions

The total rainfall from September to July was: 2013/2014 – 460.7 mm, 2014/2015 – 439.9 mm, and in 2014/2015 – 694.6 mm (Tab. 1). The following events had an adverse effect on the yield of wheat and spelt: drought in October, November, February, and May in the 2013/2014 and 2014/2015 seasons, and also in June in the 2014/2015 season. The growth of these cereals was particularly adversely affected by the shortage of rain in May and June. At that time, they were at the shooting and heading stages and exhibited an increased demand for water. In the 2015/2016 season, a precipitation deficit was recorded only in October and its excess in November, December, February, and especially in July (precipitation higher than in the multiyear period by 64%). The air temperature in the period analyzed was higher than in the multiyear period (by 0.4°C, 0.7°C, and 0.9°C, respectively). During the winter dormancy period, slight drops below 0°C did not cause the plants to freeze. After the start of vegetative growth in spring, the temperatures were generally favorable for both types of wheat (especially April 2013/2014 and 2015/2016 and May and June 2015/2016).

**Tab. 1** Temperature and precipitation during the period of study.

Growth season	Months											
	IX	X	XI	XII	I	II	III	IV	V	VI	VII	VIII
Temperature (°C)												
1	11.5	9.3	4.9	2.3	-3.5	2.0	5.5	9.5	13.3	14.8	21.0	17.9
2	14.5	9.5	4.4	-0.6	0.6	0.3	4.6	7.2	12.1	15.7	18.0	21.3
3	14.2	6.6	5.1	3.8	-3.8	2.7	3.6	8.8	14.9	18.0	18.5	17.6
Precipitation (mm)												
1	69.3	15.4	23.2	34.1	44.0	11.4	55.7	26.1	34.9	72.2	20.4	54.0
2	30.8	21.3	21.2	56.6	28.5	8.8	46.0	23.4	25.4	43.0	71.0	63.9
3	51.2	20.8	80.8	80.4	28.7	50.5	20.5	33.1	70.8	66.3	138.6	52.9

1 – growth season 2013/2014; 2 – growth season 2014/2015; 3 – growth season 2015/2016.

## Weed infestation analysis

Weed infestation analyses were performed each year in the first half of April, during the tillering stage (BBCH 22–29) and at the beginning of July during the heading stage (BBCH 55–59) of both wheat types in two randomly selected locations on each plot in the areas determined by a rectangular frame of 1 × 0.25 m. In addition, the weed species composition and population size were determined and also, during the heading stage only, their dry weight. The data were converted to a unit area basis of 1 m<sup>2</sup>. They were used to calculate the following diversity indices:

- Species richness (S);
- Simpson's domination index ( $\lambda$ ):  $\lambda = \sum p_i^2$  [10];
- Shannon–Wiener index of species diversity ( $H'$ ):  $H' = -\sum(p_i \ln p_i)$  [11];
- Pielou's evenness index ( $J'$ ):  $J' = H' \ln S^{-1}$  [12];

where  $p_i$  – proportion of individuals of the  $i$ -th species to the total size of the community and  $S$  – the number of species in the community.

## Statistical analysis

The results for the abundance, biomass and diversity indices of the weed communities were processed statistically by analysis of variance, split-plot design in 3 years

(2014–2016), according to the fixed model for factorial sets, at the level of significance  $\alpha = 0.05$ , and identifying homogenous groups with Tukey's test. The analysis of relationships between yield versus the number and dry matter of weeds in total, determined at the heading stage, as well as the four most frequently present weed species was based on Spearman's rank correlation tests. All calculations were supported by the software Statistica version 12.5.

## Results

### Number of weeds at the tillering stage

The number of weeds in spelt was significantly higher than in wheat by on average 24.3% (Tab. 2). Weed infestation of common wheat and spelt wheat during the tillering stage was greater in 2016 compared to 2014 and 2015 by almost 30% (Tab. 3). No significant influence of the forecrop on the weed infestation of common wheat was found during the three-year period analyzed. However, weed density in spelt was significantly lower (by 10.5% and 8.7%) in the field after peas, in comparison to the fields after oilseed rape and spelt. The forecrops also significantly differentiated the number of weeds in individual years. The highest weed infestation of common wheat in 2014 was observed after oilseed rape. In 2015, the weed infestation of wheat was not differentiated significantly by forecrops, and in 2016 more weeds were found in the field in which wheat succeeded wheat. The weed infestation of spelt after each of the forecrops in 2014 and 2016 was similar. Significantly fewer weeds were observed in the field after peas in 2015.

### Number of weeds in the heading stage

During the heading stage, the number of weeds in spelt was at the level determined in the tillering stage, whereas in wheat it was 23.6% higher (Tab. 3). Weed infestation of wheat and spelt was quite similar (insignificant differences; Tab. 2). However, there were significant differences between the years; in 2014 and 2015, the weed density in wheat was higher than in spelt by 30.8% and 68.6%, respectively. In 2016, more weeds were found in spelt than in wheat (almost twice as many). For those years, a significantly lower cover of weeds in the fields of both cereals was recorded after peas than after

**Tab. 2** ANOVA *F*-test statistics.

Source of variation	<i>df</i>	<i>F</i> -test statistics		
		Number of weeds		Dry matter of weeds
		Tillering stage	Heading stage	Heading stage
Years	2	284.69**	100.23**	157.56**
Error (I)	9			
Cereals	1	201.55**	1.62 <sup>ns</sup>	2.18 <sup>ns</sup>
Years × Cereals	2	1.67 <sup>ns</sup>	94.80**	96.73**
Error (II)	9			
Forecrops	2	23.13**	77.84**	37.52**
Years × Forecrops	4	47.43**	28.88**	21.10**
Cereals × Forecrops	2	14.99**	34.65**	21.14**
Years × Cereals × Forecrops	4	21.50**	24.47**	20.00**
Error (III)	36			

ns – not significant; \* significant at  $p < 0.05$ ; \*\* significant at  $p < 0.01$ .

**Tab. 3** Number of weeds in wheat and spelt (plants m<sup>2</sup>).

Growth stage	Growth season	Wheat				Spelt			
		Cereals		Forecrops		Cereals		Forecrops	
		Wheat	Spelt	Peas	Oilseed rape	Wheat	Peas	Oilseed rape	Spelt
Tillering	1	85.7 <sup>d</sup>	115.0 <sup>c</sup>	76.0 <sup>d</sup>	118.0 <sup>c</sup>	80.0 <sup>d</sup>	123.0 <sup>c</sup>	128.0 <sup>a-c</sup>	94.0 <sup>c</sup>
	2	100.3 <sup>c</sup>	128.0 <sup>b</sup>	93.0 <sup>c</sup>	110.0 <sup>c</sup>	108.0 <sup>c</sup>	91.0 <sup>d</sup>	154.0 <sup>a</sup>	139.0 <sup>ab</sup>
	3	128.3 <sup>b</sup>	148.0 <sup>a</sup>	125.0 <sup>c</sup>	125.0 <sup>c</sup>	148.0 <sup>a</sup>	151.0 <sup>a</sup>	126.0 <sup>a-c</sup>	167.0 <sup>a</sup>
	Mean	104.8 <sup>B</sup>	130.3 <sup>A</sup>	98.0 <sup>C</sup>	117.7 <sup>BC</sup>	112.0 <sup>BC</sup>	121.7 <sup>B</sup>	136.0 <sup>A</sup>	133.3 <sup>A</sup>
Heading	1	124.3 <sup>c</sup>	95.0 <sup>d</sup>	134.0 <sup>ef</sup>	130.0 <sup>ef</sup>	109.0 <sup>e-g</sup>	97.0 <sup>h</sup>	114.0 <sup>gh</sup>	74.0 <sup>hi</sup>
	2	159.0 <sup>b</sup>	94.3 <sup>d</sup>	160.0 <sup>b-e</sup>	177.0 <sup>b</sup>	140.0 <sup>d-f</sup>	35.0 <sup>i</sup>	88.0 <sup>h</sup>	160.0 <sup>bd</sup>
	3	105.3 <sup>c</sup>	206.3 <sup>a</sup>	79.0 <sup>hi</sup>	89.0 <sup>g</sup>	148.0 <sup>c-f</sup>	165.0 <sup>bc</sup>	180.0 <sup>b</sup>	274.0 <sup>a</sup>
	Mean	129.5 <sup>A</sup>	131.9 <sup>A</sup>	124.3 <sup>C</sup>	132.0 <sup>B</sup>	132.3 <sup>B</sup>	99.0 <sup>C</sup>	127.3 <sup>B</sup>	169.3 <sup>A</sup>

Values marked with the same letter do not differ significantly ( $p \leq 0.05$ ); capital letters relate to mean values for growth season and indicate comparison between wheat and spelt and comparison between these cereals and forecrops; lowercase letters relate to values for following growth season and indicate interactions between wheat and spelt and growth season and interactions between these cereals, forecrops, and growth season. 1 – growth season 2013/2014; 2 – growth season 2014/2015; 3 – growth season 2015/2016.

oilseed rape. The plots after oilseed rape and after itself at the wheat site were infested by weeds to a similar extent but there were no significant differences. Significantly more weeds were recorded at the spelt site as a result of its cultivation after itself than after peas and oilseed rape – by 71% and 33%, respectively. No significant differences were found between weed infestation of common wheat and spelt wheat after different forecrops in 2014. In 2015, it was similar in wheat cultivated after peas and oilseed rape. Significantly more weeds were found after oilseed rape than after wheat. In 2016, on the other hand, significantly fewer weeds were recorded in wheat after peas than after oilseed rape and wheat. In the years 2015 and 2016, the lowest weed density was observed at the site with spelt after peas and additionally in 2016 after oilseed rape, with the highest density in the field with spelt grown after spelt.

#### Dry matter of weeds in the heading stage

Weeds developed the lowest dry matter in 2015 (due to low rainfall in April–May). It was more than 2 times lower than in 2014 and 2016 (Tab. 2 and Tab. 4). In general, weed biomass in wheat and spelt was similar in different years (insignificant differences).

**Tab. 4** Dry matter of weeds in wheat and spelt in the heading stage (g m<sup>2</sup>).

Growth season	Wheat				Spelt			
	Cereals		Forecrops		Cereals		Forecrops	
	Wheat	Spelt	Peas	Oilseed rape	Wheat	Peas	Oilseed rape	Spelt
1	175.8 <sup>b</sup>	122.4 <sup>c</sup>	107.0 <sup>de</sup>	183.4 <sup>b</sup>	237.0 <sup>a</sup>	134.3 <sup>c</sup>	129.3 <sup>cd</sup>	103.7 <sup>e</sup>
2	79.8 <sup>d</sup>	70.8 <sup>d</sup>	60.8 <sup>g</sup>	94.0 <sup>e</sup>	84.7 <sup>f</sup>	46.7 <sup>h</sup>	80.3 <sup>f</sup>	85.3 <sup>f</sup>
3	148.2 <sup>b</sup>	219.3 <sup>a</sup>	104.7 <sup>e</sup>	158.7 <sup>bc</sup>	181.2 <sup>b</sup>	183.3 <sup>b</sup>	231.4 <sup>a</sup>	243.1 <sup>a</sup>
Mean	134.6 <sup>A</sup>	137.5 <sup>A</sup>	90.8 <sup>C</sup>	145.4 <sup>AB</sup>	167.6 <sup>A</sup>	121.4 <sup>BC</sup>	147.0 <sup>AB</sup>	144.0 <sup>AB</sup>

For explanations, see Tab. 3.

Weeds developed significantly higher dry matter in wheat than in spelt in 2014 (by 43.6%), and lower by 32.4% in 2016. In 2015, it was similar in both crops. It was observed that at sites with wheat and spelt weed biomass increased as the quality of sites deteriorated. It was higher by 84.6% and 18.6%, respectively, in the fields where the cereals succeeded themselves than peas. In wheat, weeds grew the lowest biomass after peas, and significantly higher after oilseed rape and wheat in each year of the trial (by 60.1% and 84.6%, respectively). No significant influence of forecrops on the dry matter of weeds in spelt was found. On the other hand, significant differences between forecrops in individual years were observed; in 2015 and 2016, a greater weed biomass was found in the fields after oilseed rape and spelt than in the fields after peas. In 2014, it was similar after peas and oilseed rape and it was significantly smaller after spelt.

#### Species composition of weeds in the tillering stage

Weed communities were composed mainly of annual weeds with a developmental cycle similar to that of winter wheat (Tab. 5). *Viola arvensis* dominated during the tillering stage in the communities of both cereals, with a share ranging from 37.6% to 48.2%. Significant shares were also observed for *Matricaria maritima* (9–21%) and *Capsella bursa-pastoris* (7.6–11%) as well as *Veronica arvensis* in wheat and *Fumaria officinalis* and *Veronica persica* in spelt. The wheat environment was more favorable than that of spelt for *Veronica arvensis* and that of spelt for *V. persica*. Some species were found in the field of spelt which do not occur in wheat (*Fumaria officinalis*, *Anchusa arvensis*, *Myosotis arvensis*, *Chenopodium album*, *Sonchus arvensis*, and *Vicia cracca*). Growing wheat after oilseed rape increased the population size of *M. maritima*, *Apera spica-venti*, *Thlaspi arvense*, and *Poa annua*, compared to its cultivation after peas, and decreased that of *Stellaria media*. Its cultivation after itself increased the population size of *Viola arvensis*, *C. bursa-pastoris*, and *A. spica-venti* and decreased that of *Veronica arvensis* and *S. media* compared to the fields after peas. Cultivation of spelt after oilseed rape increased the population size of *Viola arvensis*, *M. maritima*, *C. bursa-pastoris*, *S. media*, *Veronica arvensis*, *Thlaspi arvense*, and *A. spica-venti* compared to cultivation after peas. *Sonchus arvensis* was found on this plot, which did not occur in the field after peas. Increased occurrence of *Viola arvensis*, *M. maritima*, *C. bursa-pastoris*, *T. arvense*, and *A. spica-venti* was observed in the field where this cereal succeeded itself. This site limited the occurrence of *Veronica persica* and *Lamium amplexicaule*.

#### Species composition of weeds in the heading stage

*Viola arvensis* dominated in the heading stage, both in wheat and spelt; it accounted for 39.2% to 45.1% of the total number of weeds (Tab. 6). It was followed by *A. spica-venti*, with a share ranging from 22.7% to 35.9%. *Veronica arvensis* was also found in significant numbers in wheat (between 16.9% and 19.1%) and *C. bursa-pastoris* in both cereals (between 5.1% and 10.4%). The density of *A. spica-venti* and *C. bursa-pastoris* was higher in spelt than in wheat, whereas that of *Veronica arvensis* and *Geranium pusillum* was lower. The forecrops did not significantly differentiate the number of weeds in wheat. The cultivation of spelt after oilseed rape, and particularly after spelt, increased the population sizes of *Viola arvensis*, *A. spica-venti*, and *Veronica arvensis*, and cultivation after peas, population sizes of *Matricaria discoidea* and *Poa annua*.

The largest share of the dry matter of weeds in wheat was found for *Viola arvensis* (34–47.4%), *A. spica-venti* (21.6–24%), and *C. bursa-pastoris* (16.1–23.7%) and in spelt, *A. spica-venti* (26.1–42.6%), *Viola arvensis* (27.3–37.8%), *C. bursa-pastoris* (4.8–10.2%), and *Centaurea cyanus* (1.7–14.4%). The environment of spelt was more favorable than that of wheat for the development of *A. spica-venti*, *C. cyanus*, and *M. maritima*, whereas it restricted the growth of *Viola arvensis*, *C. bursa-pastoris*, and *Veronica arvensis*. Growing wheat after oilseed rape and after wheat increased (compared to growing it after peas) the share in the weed biomass of *Viola arvensis* (by >30%), *A. spica-venti*, and *C. bursa-pastoris* (ca. twofold for these two species) and *M. discoidea* and *Geranium pusillum*. An increase was observed in the share of *Viola arvensis* (by 46.1% and 64.2%), *A. spica-venti* (43.8% and 93.7%), and *Veronica arvensis* in the weed biomass in spelt

**Tab. 5** Species composition and number of weeds in wheat and spelt in tillering stage (plants m<sup>2</sup>), mean for years 2014–2016.

Species	Forecrops			Mean
	Peas	Oilseed rape	Wheat	
	<b>Wheat</b>			
<i>Viola arvensis</i> Murray	44.3	46.3	54.0	48.2
<i>Matricaria maritima</i> L. subsp. <i>inodora</i> (L.) Dostál	13.7	24.7	14.3	17.6
<i>Veronica anversis</i> L.	12.3	13.0	9.3	11.5
<i>Capsella bursa-pastoris</i> (L.) Medik	8.0	10.7	12.0	10.2
<i>Stellaria media</i> (L.) Vill.	8.3	6.0	6.3	6.9
<i>Apera spica-venti</i> (L.) P. Beauv.	2.0	5.0	7.0	4.7
<i>Geranium pusillum</i> Burm. F. ex L.	2.7	3.0	3.3	3.0
<i>Thlaspi arvense</i> L.	1.7	4.0	2.3	2.7
<i>Poa annua</i> L.	1.7	3.0	1.8	2.2
<i>Centaurea cynaus</i> L.	1.0	1.5	0.4	1.0
<i>Veronica persica</i> Poir.	2.0	-	-	0.6
<i>Lamium amplexicaule</i> L.	0.3	0.5	0.8	0.5
<i>Galium aparine</i> L.	-	-	0.5	0.1
	<b>Spelt</b>			
<i>Viola arvensis</i> Murray	45.7	58.8	50.3	51.6
<i>Matricaria maritima</i> L. subsp. <i>inodora</i> (L.) Dostál	11.0	24.3	20.3	18.5
<i>Capsella bursa-pastoris</i> (L.) Medik	9.3	15.0	14.0	12.8
<i>Veronica persica</i> Poir.	14.0	6.0	8.7	9.6
<i>Fumaria officinalis</i> L.	13.0	-	11.0	8.0
<i>Stellaria media</i> (L.) Vill.	3.3	5.7	4.7	4.6
<i>Veronica arvensis</i> L.	2.7	7.7	1.0	3.8
<i>Centaurea cynaus</i> L.	4.0	2.0	3.7	3.2
<i>Thlaspi arvense</i> L.	0.7	3.5	5.3	3.2
<i>Apera spica-venti</i> (L.) P. Beauv.	1.0	4.5	3.0	2.8
<i>Galium aparine</i> L.	4.0	-	3.0	2.3
<i>Lamium amplexicaule</i> L.	3.0	2.0	1.0	2.0
<i>Anchusa arvensis</i> (L.) M. Bieb.	2.7	-	1.7	1.5
<i>Myosotis arvensis</i> (L.) Hill	2.7	0.5	1.3	1.5
<i>Chenopodium album</i> L.	1.3	1.0	2.3	1.5
<i>Geranium pusillum</i> Burm. F. ex L.	1.0	1.0	1.3	1.1
<i>Poa annua</i> L.	2.0	1.0	-	1.0
<i>Sonchus arvensis</i> L.	-	3.0	0.7	0.3
<i>Vicia cracca</i> L.	0.3	-	-	0.1

**Tab. 6** Species composition, number of weeds (plants m<sup>2</sup>), and dry matter of weeds (g m<sup>2</sup>) in wheat and spelt in heading stage (plants m<sup>2</sup>), mean for years 2014–2016.

Species	Number				Dry matter			
	Forecrops							
	Peas	Oilseed rape	Cereal	Mean	Peas	Oilseed rape	Cereal	Mean
<b>Wheat</b>								
<i>Viola arvensis</i> Murray	52.3	51.7	57.3	53.8	43.0	55.6	57.0	51.9
<i>Apera spica-venti</i> (L.) P. Beauv.	30.3	36.7	30.0	32.3	19.6	34.9	40.3	31.6
<i>Veronica arvensis</i> L.	23.7	23.0	22.4	23.0	8.5	7.6	8.3	8.1
<i>Capsella bursa-pastoris</i> (L.) Medik	7.7	6.7	8.7	7.7	14.6	34.4	32.9	27.3
<i>Geranium pusillum</i> Burm. F. ex L.	6.0	8.3	3.7	6.0	2.5	4.7	4.9	4.0
<i>Matricaria discoidea</i> DC.	2.0	2.0	3.3	2.4	1.5	5.4	4.3	3.7
<i>Poa annua</i> L.	0.7	0.7	2.3	1.2	0.2	0.3	0.4	0.3
<i>Matricaria maritima</i> L. subsp. <i>inodora</i> (L.) Dostál	-	2.0	1.3	1.1	0.1	1.3	0.5	0.6
<i>Sinapis arvensis</i> L.	1.3	-	1.3	0.8	0.6	-	0.7	0.4
<i>Fumaria officinalis</i> L.	-	-	0.7	0.2	-	-	0.3	0.1
<i>Lamium amplexicaule</i> L.	0.3	-	-	0.1	0.1	-	-	0.1
<i>Chenopodium album</i> L.	-	-	0.7	0.2	-	-	0.4	0.1
<i>Thlaspi arvense</i> L.	-	0.6	-	0.2	-	0.2	-	0.1
<i>Centaurea cyanus</i> L.	-	-	0.3	0.1	-	-	3.6	1.2
<i>Anchusa arvensis</i> L.	-	-	0.3	0.1	-	-	13.1	4.4
<i>Veronica persica</i> Poir.	-	0.3	-	0.1	-	0.1	-	0.1
<i>Stellaria media</i> (L.) Vill.	*	*	*	*	0.1	0.9	0.9	0.6
<b>Spelt</b>								
<i>Viola arvensis</i> Murray	42.0	50.0	76.3	56.1	33.2	48.5	54.5	45.4
<i>Apera spica-venti</i> (L.) P. Beauv.	26.7	45.7	59.0	43.8	31.7	45.6	61.4	46.2
<i>Capsella bursa-pastoris</i> (L.) Medik	10.3	8.7	14.3	11.1	12.0	7.0	14.7	11.2
<i>Veronica arvensis</i> L.	4.3	9.0	13.0	8.8	0.9	3.1	4.3	2.8
<i>Centaurea cyanus</i> L.	2.3	1.7	1.0	1.7	16.0	21.1	2.5	13.2
<i>Matricaria discoidea</i> DC.	5.3	1.3	0.3	2.3	6.8	0.8	0.1	2.6
<i>Poa annua</i> L.	4.0	1.7	1.7	2.5	2.2	1.9	0.6	1.6
<i>Matricaria maritima</i> L. subsp. <i>inodora</i> (L.) Dostál	2.0	3.0	2.3	2.4	17.8	13.9	4.4	12.0
<i>Lamium amplexicaule</i> L.	0.4	1.7	-	0.7	0.1	0.7	-	0.3
<i>Geranium pusillum</i> Burm. F. ex L.	0.5	3.3	1.0	2.4	0.1	3.7	1.4	1.7
<i>Stellaria media</i> (L.) Vill.	-	0.7	-	0.2	-	0.6	-	0.2
<i>Myosotis arvensis</i> (L.) Hill	0.7	-	-	0.2	0.5	-	-	0.1
<i>Polygonum lapathifolium</i> L.	0.5	1.3	-	0.6	0.1	0.1	-	0.1
<i>Polygonum aviculare</i> L.	-	-	0.4	0.1	-	-	0.1	0.1

\* Not marked.



after oilseed rape and spelt, and that of *C. cyanus* after oilseed rape. Growing spelt after spelt did not favour *M. discoidea*, *M. maritima*, or *C. cyanus*, and after oilseed rape, *C. bursa-pastoris* or *M. discoidea*.

### Biodiversity indicators for weed communities

In the tillering stage, the number of weed species was larger in spelt than in wheat fields. At the heading stage, it was similar in both crops (Tab. 7). The forecrops were not found to affect the population sizes of weeds during either of the periods under study. Weed communities during the wheat and spelt heading stage were characterized by similar dominance (insignificant differences). In spelt, however, they were more diverse, but at the same time they were characterized by a lower evenness of distribution of individuals among populations. In the heading stage, significantly higher species dominance was observed in fields of spelt than in those of wheat. The wheat species did not significantly influence the diversity or evenness of the communities under study. The forecrops did not significantly differentiate the dominance index in wheat and spelt. During the tillering stage, the diversity index was found to decrease in both cereals when they were grown after themselves. In wheat, the most favorable distribution of individuals among species occurred after peas and the least favorable was after wheat. In spelt, this feature was not affected by the forecrops. These indices were different during the heading stage. The most diverse community in wheat was observed in the fields where it was grown after wheat. The distribution of individuals among populations was similar at all sites. For spelt, in turn, the lowest diversity and evenness was observed in the community in the field where it was grown after spelt. The remaining sites did not exhibit any significant differences in this regard.

Tab. 7 Biodiversity indicators for weed communities, mean for years 2014–2016.

Cereals	Forecrops	Tillering				Heading			
		Indicators*							
		S	$\lambda$	$H'$	$J'$	S	$\lambda$	$H'$	$J'$
Wheat	Peas	12 <sup>b</sup>	0.256 <sup>a</sup>	1.770 <sup>a</sup>	0.851 <sup>a</sup>	10 <sup>a</sup>	0.196 <sup>a</sup>	1.479 <sup>b</sup>	0.617 <sup>a</sup>
	Oilseed rape	11 <sup>b</sup>	0.226 <sup>a</sup>	1.823 <sup>a</sup>	0.760 <sup>b</sup>	11 <sup>a</sup>	0.268 <sup>a</sup>	1.553 <sup>ab</sup>	0.648 <sup>a</sup>
	Wheat	12 <sup>b</sup>	0.276 <sup>a</sup>	1.474 <sup>b</sup>	0.575 <sup>c</sup>	14 <sup>a</sup>	0.193 <sup>a</sup>	1.617 <sup>a</sup>	0.630 <sup>a</sup>
Spelt	Peas	18 <sup>a</sup>	0.277 <sup>a</sup>	1.867 <sup>a</sup>	0.646 <sup>a</sup>	12 <sup>a</sup>	0.273 <sup>a</sup>	1.637 <sup>a</sup>	0.659 <sup>a</sup>
	Oilseed rape	15 <sup>a</sup>	0.241 <sup>a</sup>	1.891 <sup>a</sup>	0.698 <sup>a</sup>	12 <sup>a</sup>	0.282 <sup>a</sup>	1.613 <sup>a</sup>	0.649 <sup>a</sup>
	Spelt	17 <sup>a</sup>	0.273 <sup>a</sup>	1.704 <sup>b</sup>	0.602 <sup>a</sup>	10 <sup>a</sup>	0.338 <sup>a</sup>	1.277 <sup>b</sup>	0.555 <sup>b</sup>
Mean for wheat		12 <sup>B</sup>	0.238 <sup>A</sup>	1.714 <sup>B</sup>	0.730 <sup>A</sup>	12 <sup>A</sup>	0.184 <sup>B</sup>	1.548 <sup>A</sup>	0.623 <sup>A</sup>
Mean for spelt		17 <sup>A</sup>	0.278 <sup>A</sup>	1.803 <sup>A</sup>	0.632 <sup>B</sup>	11 <sup>A</sup>	0.302 <sup>A</sup>	1.479 <sup>A</sup>	0.625 <sup>A</sup>

Values marked with the same letter do not differ significantly ( $p \leq 0.05$ ); capital letters indicate comparison between wheat and spelt; lowercase letters indicate comparison between these cereals and forecrops. \* S – species richness;  $\lambda$  – Simpson's dominance index;  $H'$  – Shannon–Wiener's species diversity index;  $J'$  – Pielou's evenness index.

### Correlation between weeds infestation and yield

For wheat cultivated after peas, the yield was positively correlated with the total number of weeds, the number of *Veronica arvensis* and number and dry weight of *A. spica-venti* (Tab. 8). A negative correlation was found between the yield and the number and dry matter of *A. spica-venti*, dry matter of *Viola arvensis* at the site where wheat was grown after oilseed rape, and with the total dry matter of weeds and dry matter of *C. bursa-pastoris* in the field where wheat was grown after wheat. A significant positive correlation was observed between yield, number, and biomass of *Veronica arvensis* and in the field after oilseed rape also between yield and *C. bursa-pastoris*. At the site where

**Tab. 8** Spearman rank order correlations matrix between yield of wheat and number and dry matter of weeds in the heading stage ( $n = 12$ ).

Forecrops	Total	<i>Viola arvensis</i>	<i>Apera spica-venti</i>	<i>Veronica arvensis</i>	<i>Capsella bursa-pastoris</i>
Number					
Peas	0.74**	-0.21	0.73**	0.76**	0.10
Oilseed rape	0.19	-0.29	-0.77**	0.73**	0.67*
Wheat	-0.25	-0.45	-0.51*	0.60*	-0.23
Dry matter					
Peas	0.04	-0.50	0.60*	0.56	0.29
Oilseed rape	-0.04	-0.64*	-0.86**	0.67*	0.60*
Wheat	-0.64*	-0.90**	-0.53*	0.77**	-0.61*

\* Significant at  $p < 0.05$ ; \*\* significant at  $p < 0.01$ .

**Tab. 9** Spearman rank order correlations matrix between yield of spelt and number and dry matter of weeds in the heading stage ( $n = 12$ ).

Forecrops	Total	<i>Viola arvensis</i>	<i>Apera spica-venti</i>	<i>Veronica arvensis</i>	<i>Capsella bursa-pastoris</i>
Number					
Peas	-0.42	-0.50	-0.92**	-0.13	0.82**
Oilseed rape	-0.46	-0.90**	-0.54	0.45	0.76**
Spelt	-0.93**	-0.87**	-0.87**	0.42	0.43
Dry matter					
Peas	-0.47	-0.48	-0.90**	0.16	0.84**
Oilseed rape	-0.43	-0.84**	-0.60*	0.93**	0.78**
Spelt	-0.91**	-0.91*	-0.90**	0.44	0.47

\* Significant at  $p < 0.05$ ; \*\* significant at  $p < 0.01$ .

spelt was grown after peas and after oilseed rape, the yield was positively correlated with the number and biomass of *C. bursa-pastoris*, and after oilseed rape, also with *Veronica arvensis* (Tab. 9). The decrease in the yield on the field with spelt cultivation was accompanied by an increase in the number and dry matter of all weeds. The yield was negatively correlated with the number and biomass of *Viola arvensis* at the site where the crops were grown after oilseed rape and after themselves and with *A. spica-venti* at all sites (except for the population size of the weed after oilseed rape, where only a trend was noted).

## Discussion

### Weed infestation of common wheat and spelt wheat

Our study has shown that the number and biomass of weeds in common wheat and spelt wheat were more dependent on weather conditions during the growing season than on the other factors examined in our trial. Blackshaw et al. [1], Demjanová [13], and Doucet et al. [14] are also of the opinion that weather has a greater effect on weed

infestation than the crop sequence. In our study, more weeds were recorded in the humid year 2016 compared to the 2 previous ones with moderate rainfall, which is consistent with the findings of Seibutis and Deveikyte [6]. Weed infestation was higher in the spelt field than in the wheat field only during the tillering stage. During the heading stage, weed infestation was similar in both types of wheat. Opinions in the literature on the competitiveness of both wheats against weeds are divided. There are reports both about the extent of dominance of weeds and the degree [15,16]. According to Feledyn-Szewczyk [16], old cultivars of wheat (including spelt) compete more effectively against weeds, whereas modern cultivars (such as 'Rokosz', as in the present study), do so similarly to common wheat or less strongly. It depends mainly on the density and intrinsic genotypic features, such as tillering, height, leaf surface area, and the angle the leaves are held on the stem. In our study, spelt was found to have a greater height than common wheat, but its tillering was lower and its foliage weaker, which resulted in the fact that both subspecies were similarly infested by weeds.

### Role of forecrops

No effect was found of the forecrops on weed population size in common wheat during the tillering stage, as opposed to spelt, where a significantly higher abundance of weeds was recorded in the field after rape and spelt. During the heading stage, a higher weed infestation of both types of wheat occurred in the fields when they were grown after rape and after themselves than in the fields after peas. Peas as a forecrop were characterized each year by the compactness of the stand and abundant foliage, which effectively limited the development of weeds and the shedding of their seeds onto the soil. At the same time, the forecrop had a positive effect on the soil environment, which was reflected in a higher density and fertility of wheat and spelt plants, which made them better able to compete with weeds. A positive effect of the legumes on the soil was confirmed by Danga et al. [17]. For wheat, the fields after rape and wheat exhibited similar weed infestation and, in the case of spelt, significantly more weeds were recorded after spelt than after rape. The increase in weed infestation of the field after rape was a result of the sequence of two winter species, which favored the continuity of occurrence of weeds with a similar developmental cycle in that field. Moreover, the density of both crops after this forecrop and their height and foliage were smaller than after peas, which made them less competitive against weeds (our unpublished data). Seibutis and Deveikyte [6] also reported higher weed infestation of winter wheat grown after winter rape. These authors showed that alternating cultivation of winter crops with spring crops can even reduce weed infestation by a half. Our findings confirmed the literature that growing wheat after wheat leads to an increase in weed infestation [1,6,18–20]. The soil environment is then degraded due to the accumulation of harmful secondary metabolites and changes in the structure of microorganism communities. This weakens the condition of the cereals, adversely affecting their density, tillering, foliage development, and growth, which makes them less competitive with weeds [21]. However, a different view is presented by Santín-Montanyá et al. [22] who claimed that the crop sequence does not have a significant effect on weed density.

### Weed communities

In the spelt fields, more favorable conditions for development were found for *A. spica-venti*, *C. cyanus*, and *M. maritima* than in wheat, and worse for *Viola arvensis*, *C. bursa-pastoris*, and *Veronica arvensis*. In our previous research, weed communities in spelt were characterized by a higher species richness than in wheat but only at the tillering stage. After all the forecrops tested, they comprised a similar number of species, which is consistent with the findings of Demianová [13] and Doucet et al. [14]. Liebman and Dyck [23] and Santín-Montanyá [22] are of a different opinion, arguing that a faulty crop sequence in wheat cultivation can lead to decreased diversity in a weed community and it being dominated by several species. In our research, the dominant weeds in both crops accounted for 82–90% of all weeds. These included *Viola arvensis*, *A. spica-venti*, *C. bursa-pastoris*, in wheat also *Veronica arvensis*, and in spelt, *C. cyanus*

and *M. maritima*. A similar set of dominants is mentioned in the paper by Seibutis and Deveikyte [6]. Buhler et al. [24] argue that dominants are the main pests of crops, as they are generally resistant to plant protection products and adapt easily to the plant cultivation system.

In our own research, we observed an increase in the population of *A. spica-venti* in both the cereals grown after oilseed rape and after themselves, and in the latter case, also *Viola arvensis*; additionally in wheat, also *C. bursa-pastoris*. In similar climatic and soil conditions, an increase in the occurrence of *A. spica-venti* was observed by Melander et al. [25] and Małecka-Jankowiak et al. [20] in crop rotations when winter wheat was grown after winter oilseed rape and after itself. Koocheki et al. [18] argue that the greater abundance of some weed species results from their morphological similarity to cultivated plants and a similar developmental cycle, which can be observed in *A. spica-venti*. This aggressive weed sheds a large number of diaspores onto the soil, which can survive for up to 2 years in the soil; it also occurs in less compact stands [21]. A larger population size of *Viola arvensis* and *C. bursa-pastoris* in the winter wheat monoculture is also reported by Kwiatkowski [19]. It is difficult to make conclusions about the dominance of other weed species at the sites under assessment as they were different species under different habitat conditions.

## Conclusions

Weed species richness in spelt was higher than in common wheat during the tillering stage. Weed infestation of common wheat and spelt was similar during the heading stage. The lowest weed infestation in both crops was observed on the field where peas had been grown. Growing wheat and spelt after oilseed rape and, especially after themselves, were the reason for an increase in weed infestation. Biomass of weeds in a field of spelt was similar after all forecrops unlike in wheat, where more biomass was observed after oilseed rape and wheat. Spelt was more favorable than wheat for the growth of *A. spica-venti*, *C. cyanus*, and *M. maritima*, and it limited the growth of *Viola arvensis*, *C. bursa-pastoris*, and *Veronica arvensis*. A greater frequency of *A. spica-venti* and *Viola arvensis* was observed in common wheat and spelt grown after oilseed rape and after itself, and in wheat only, *C. bursa-pastoris*, *M. discoidea*, and *G. pusillum*. In spelt grown after oilseed rape, it was *C. cyanus*, and after itself, *Veronica arvensis*. Weed communities in spelt were more diverse than in wheat. However, the distribution of individuals in populations was less even. The forecrop did not differentiate the species diversity in either crop. The weed diversity in fields of both crops was lower in the field when they were grown after themselves only during the tillering stage.

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## Bioróżnorodność zbiorowisk chwastów w pszenicy zwyczajnej i pszenicy orkisz w uprawie po różnych przedplonach

### Streszczenie

W technologiach uprawy roślin coraz częściej stosuje się rozwiązania przyjazne dla środowiska. Są nimi m. in. powrót do uprawy dawnych roślin (np. pszenicy orkisz), czy też stosowanie rotacji. Zapewnienie odpowiedniego przedplonu jest szczególnie ważne dla pszenicy ozimej, która jest rośliną podatną na zachwaszczenie. Niewiele informacji znajdujemy natomiast na temat zachwaszczenia orkisz ozimego. W pracy założono, że zboże to w mniejszym stopniu niż pszenica ulegnie inwazji chwastów, zwłaszcza po niekorzystnych dla niego przedplonach. Podstawę badań stanowiło doświadczenie polowe, realizowane w stacji badawczej Uniwersytetu Warmińsko-Mazurskiego w Olsztynie. Celem badań było porównanie zachwaszczenia pszenicy zwyczajnej i pszenicy orkisz uprawianych po przedplonach: grochu siewnym, rzepaku ozimym i po sobie. Analizy zachwaszczenia przeprowadzono w latach 2014–2016 w fazach rozwojowych pszenic: krzewienie (BBCH 22–29) i kłoszenie (BBCH 55–59). Oznaczano skład gatunkowy i liczebność gatunków chwastów, a w fazie kłoszenia także ich suchą masę. Wyliczono też wskaźniki: bogactwa gatunkowego ( $S$ ), dominacji Simpsona ( $\lambda$ ), różnorodności gatunkowej Shannona–Wienera ( $H'$ ) oraz równomierności Pielou ( $J$ ). Pszenica orkisz odznaczała się większym zachwaszczeniem od pszenicy zwyczajnej w fazie krzewienia (o prawie 20%). W fazie kłoszenia zachwaszczenie obu pszenic było podobne. W przypadku pszenicy i orkiszu najmniejsze zachwaszczenie stwierdzono w uprawie po grochu. Uprawa po rzepaku ozimym i po sobie prowadziła do wzrostu zagęszczenia chwastów. Biomasa chwastów w łanie orkiszu po wszystkich przedplonach była podobna, w przeciwieństwie do pszenicy, gdzie większą biomasę stwierdzono po rzepaku i pszenicy. W pszenicy zwyczajnej i pszenicy orkisz uprawianych po rzepaku ozimym i po sobie odnotowano większy udział *Apera spica-venti* i *Viola arvensis*. Zbiorowiska chwastów w orkiszu były bardziej różnorodne niż w pszenicy. Przedplony nie różnicowały bogactwa gatunkowego chwastów w obu zbożach.