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Competitiveness indicators of herbicide silky bentgrass (*Apera spica-venti* L.) of different susceptibility to herbicides toward winter wheat

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Abstract

Silky bentgrass (*Apera spica-venti* L.) is one of Central Europe's most troublesome monocotyledonous weeds of winter crops. This study aimed to analyze the competitiveness of biotypes of silky bentgrass against winter wheat, depending on the type of soil substrate and nitrogen fertilization. In this research, in a pot experiment during two seasons, the effect of bentgrass plants, of different sensitivity/resistance to herbicides, on winter wheat was studied in an additive model. It was carried out on sandy or clay soil, either non-fertilized or fertilized with nitrogen. The competitive indices were calculated based on several wheat morphological and yield features. Multivariate analysis was incorporated to interpret the data. As a result, it was found that wheat performance was affected by bentgrass competition. No clear effect of soil type and nitrogen fertilization on the competitiveness of *A. spica-venti* biotypes was demonstrated. Only in one season was the pyroxsulam-resistant biotype competitive to the winter wheat when grown on fertilized clay soil. Further research with varied numbers of winter wheat and bentgrass is advised to assess crop-weed effects further.

Keywords: additive competition model, crop performance, herbicide resistance

Introduction

Every weed population is diverse to a greater or lesser extent, and it is composed of individuals (biotypes) that react differently to herbicides. Both herbicide-sensitive and resistant biotypes may appear in the canopy of a cultivated plant in various quantitative ratios (Gaines *et al*. 2020). Between biotypes in the weed population and between the weed and the crop plant, there is competition for space, light, water, and nutrients (Kumar and Jha 2015; Osipitan and Dille 2017; Mobli *et al*. 2020). The competitive abilities of weeds toward crops are influenced by ecophysiological indicators of plants such as photosynthetic productivity, the plant's ability to absorb water and nutrients, growth and developmental dynamics, plant size, number of leaves, number of inflorescences and plant fertility, and biomass accumulation. These indicators may depend on the environment in which the weed develops, their physiological and biochemical adaptation, and stress conditions resulting from herbicide application (Du *et al*. 2019). Literature reports indicate that weeds with an herbicide resistance gene show lower viability and reduced values of ecophysiological indicators (Leroux 1993; Baucom and Mauricio 2004).

Since competition is highly complex, several methods have been developed to define competition between weed biotypes and crop plants. These methods consider the species proportions and spatial arrangement of plants, which allows for distinguishing the interspecific and intraspecific competition levels, considering weather conditions and soil type (Swanton *et al.* 2015).

Research on competitiveness can provide valuable information for farmers and producers of plant protection products (Beckie and Harker 2017; Perotti *et al.* 2020). They also constitute an important aspect of research on the ecology and physiology of plants in terms of the morphological and physiological costs associated with the acquisition of herbicide resistance and the invasive potential of resistant biotypes (Fernando *et al.* 2016; Piasecki *et al.* 2019).

One of Central Europe's most troublesome monocotyledonous weeds of winter crops is silky bentgrass (*Apera spica-venti* L.) (Auškalnienė *et al.* 2020; Košnarová *et al.* 2021). A high genetic variability characterizes this species because of cross-pollination and wind dispersal of tiny seeds. As a result, populations of silky bentgrass display variable sensitivity to herbicides, with many herbicide-resistant biotypes (Rola and Marczewska 2002; Wrzesińska *et al.* 2021; Petersen and Raffael 2022). Due to the significance of this weed in agricultural production, it is important to elaborate more on its competitive abilities toward crops.

Particularly important, from the point of view of weed control strategy management, is to conduct research on the behavior of sensitive and resistant biotypes in interspecific competition with crop plants, especially under field conditions (Cousens and Fournier-Level 2018; Travlos *et al.* 2020). The competitiveness of weeds may vary significantly depending on the biotype (Cousens and Fournier-Level 2018). Weeds are one of the main limitations to yield in agricultural production (Latif *et al.* 2021). Several methods have been developed to define competition between weed biotypes and crop plants. Such experiments aim to identify the most competitive biotypes or species (Oliveira *et al.* 2014, 2018). Currently existing methods of studying the interaction between plants are based on the assumptions of model experiments, most often field experiments, which assess competitiveness based on the relative response of plants or express the strength of competitiveness based on relative competitiveness indicators determined for each of the adopted models (Radosevich 1987; Bagavathiannan *et al.* 2011; Aslani and Saeedipour 2015; Knezevic and Datta 2015; Swanton *et al.* 2015; Kumar and Jha 2016; Shrestha *et al.* 2018). These models take into consideration variable parameters such as plant density, spatial arrangement of plants, and the proportion of each tested species in the mixture, which allows for distinguishing the level of inter- and intra-specific competition. Such factors as weather conditions and soil type are also considered (Swanton *et al.* 2015). The most frequently used system to study the competitiveness between weeds and crop plants is the additive model (Cousens 1985; Weaver and Ivany 1998; Banik *et al.* 2006; Sanjani *et al.* 2009; Bantie *et al.* 2014; Knezevic and Datta 2015; Guglielmini *et al.* 2017). In this model, the research object contains a fixed number of crop plants and a selected number of weeds, the size of which can be changed depending on the research assumptions (Bantie *et al.* 2014; Bitew and Asargew 2014). This system reflects most situations in agricultural fields with a specific and uniform crop population, but varying weed density (Swanton *et al.* 2015). With this experimental scheme the percentage of yield losses (or other measured plant characteristics) as weed density increases can be determined (Guglielmini *et al.* 2017). Most often, it is used to determine the economic threshold of weed noxiousness and the potential yield of crops (Oliveira *et al.* 2018).

In this experiment it was assumed that soil type (clay or sandy) and nitrogen fertilization modify the competitiveness of bentgrass (*Apera spica-venti* L.) of different herbicide resistance/sensitivity levels with winter wheat. The study aimed to analyze the competitiveness of biotypes of silky bentgrass against winter wheat, depending on the type of soil substrate and nitrogen fertilization.

Materials and Methods

Five silky bentgrass biotypes were used in the research: three herbicide-resistant and two herbicide-sensitive (Table 1). The populations were selected based on the herbicide-resistance type, considering that in Poland, most bentgrass populations are resistant to herbicides, mostly from the HRAC/WSSA 2 group (Adamczewski *et al.* 2019). Until the experiment was carried out, bentgrass seeds were stored at a temperature of 4°C.

The experiment was carried out in a vegetation hall in the 2018/2019 and 2019/2020 seasons with access to rainwater and natural air circulation. The experiment was set up in a completely randomized design, with three repetitions. Five biotypes of bentgrass were used in the experiment (Table 1). Biological tests have previously confirmed the resistance or sensitivity of bentgrass biotypes to herbicides. Bentgrass competed with winter wheat cv. Arkadia (breeder Danko Hodowla Plant Sp. z o.o.). Each pot contained a fixed number of plants: 30 wheat plants and five plants of one of the mentioned bentgrass biotypes. The control (K PZ) had pots containing only 30 wheat plants. Winter wheat

Table 1. Characteristics of silky bentgrass biotypes (*Apera spica-venti* (L.) P. Beauv.) used in the pot experiment (based on Jop *et al.* 2024)

Biotype	Resistance type	Herbicide	HRAC/WSSA group	RI	Collection year	Collection site
B1	single	pyroxsulam	2	R	2016	Czech Republic
B2	single	iodosulfuron methyl sodium	2	R	2017	Wądroże Małe (Poland) 51°03′44″N 16°18′38″E
AB	multiple	fenoxaprop-P / chlorsulfuron/ iodosulfuron methyl sodium/ mesosulfuron methyl	1 2 2 2	RR RR RRR RR	2013	Nowa Cerkiew (Poland) 53°51′58″N; 18°39′27″E
S1	--	sensitive	-	S	2012	Sitno (Poland) 53°11′10″N; 16°01′46″E
S2	--	sensitive	-	S	2016	Poland

*resistance type – according to WSSA (1998)
Legend: RI – Resistance Index (S – susceptible; R – low resistance; RR – moderate resistance; RRR – high resistance). Pot experiment

grains were point-sown according to the optimal density specified by the breeder (375 pcs. per 1 square meter) into 18-liter plastic pots (top diameter 31 cm, bottom diameter 25 cm, height 27 cm).

The pots were filled with soil substrates: an arable layer of brown soil with a granulometric composition of sandy loam (marked as S) and an arable layer of brown soil with a granulometric composition of clay loam (marked as C). Characteristics of soil S: pH – 5.4; P_2O_5 – 13.8 mg · 100 g^{-1}; K_2O – 9.5 mg · 100 g^{-1}; N – 0.1%. Characteristics of soil C: pH – 6.7; P_2O_5 – 9.1 mg · 100 g^{-1}; K_2O – 15.6 mg · 100 g^{-1}; N – 0.1%. Half of the pots (marked as a1) were fertilized with Polifoska M fertilizer (NPK(MgS) 5-16-24-(4-7)) at a dose equivalent to 300 kg N · ha^{-1} in summer and with ammonium nitrate 34 N in the wheat BBCH 30–31 in spring at a dose equivalent to 250 kg · ha^{-1}. The other half of the pots were without fertilization (marked as a0). During the season, other weeds were removed from the pots. Manual soil irrigation was provided when the soil substrate stopped adhering tightly to the edges of pots. Each pot was given enough water to moisten the substrate and reattach it to the edges. Watering continued until precipitation occurred.

Plants were harvested on July 14, 2019, July 14, 2020 (silky bentgrass), July 21, 2019, and July 21, 2020 (winter wheat). First, the weed was collected to prevent its seeds from falling. Winter wheat plants were collected from each pot. Wheat biometric measurements included stem length DP (cm), number of stems per plant LZZ and number of ears per plant LKR, number of stem internodes LMZ, ear length DK (cm), biomass of plant BR (g per pot), and biomass of roots BK (g per pot). The grain analysis included ear mass MJK (g), number of grains per ear LZK, number of grains per plant LZ, mass of grains PZ (g per pot), and mass of a thousand grains MTZ (g). Wheat plants were measured immediately after harvest. Length was measured using a ruler with a millimeter scale. To determine the weight of the roots, they were rinsed under running water, dried with a paper towel, and then weighed. The absolute dry mass of the aboveground parts and roots of plants and grains of winter wheat was determined after drying in a laboratory dryer at 105°C for 8 hours. The mass of wheat grains and the biomass of the aboveground parts and roots were then standardized to 15% humidity.

Competitiveness indicators

Based on the results of morphological and biometric measurements of wheat plants and yield analysis, an assessment of the relative competitiveness of weeds concerning the crop was carried out according to selected competitiveness indicators (Rudnicki and Jaskulski 2006):

Crop characteristics impacted by weeds Kcu assesses the relative difference in the value of the characteristics of a single crop plant (P), e.g., number of ears, ear length on a weed-free treatment (b) related to a weed-infested treatment (a), according to the formula:

$$Kcu = (Pb - Pa) \times 100 / Pb \ (\%).$$

Crop displacement by weeds Kwu assesses the relative difference in stem density (S) of a crop plant with a weed-free treatment (b) related to a weed-infested treatment (a), according to the formula:

$$Kwu = (Sb - Sa) \times 100 / Sb \ (\%).$$

Crop productivity impacted by weeds Kou assesses the relative difference in the biomass/yield of a crop plant (B) with a weed-free treatment (b) related to a weed-infested treatment (a), according to the formula:

$$Kou = (Bb - Ba) \times 100 / Bb \ (\%).$$

The indicators mentioned above make it possible to assess the effects of the competitive impact of weeds on a crop plant, expressed as a percentage. A higher positive value of each indicator indicates stronger weeds' competition toward crops. The value of indicators equal to zero or near zero (< 0.5) designates a lack of competition between plants. A negative indicator value indicates the stimulating effect of weeds on crops (Rudnicki and Jaskulski 2006). For control objects (without weeds), the indicators have a value of 0%. Additionally, the indicators Kcu (for the number of ears per plant) and Kwu (for the number of stems per plant) may be equal when all the crop stems have an ear.

Statistical analysis

According to Rudnicki and Jaskulski (2006), the analysis of the relative competitiveness of the S and R biotypes of bentgrass on winter wheat was based on the arithmetic mean values of a given indicator, calculated for the analyzed measurements. Then, the average values of the indicators were subjected to cluster analysis, which included all indicators tested in a given series of experiments. Clusters were created using the Ward method (1963), and the results were presented graphically in the form of a dendrogram in the Statistica 13.0 software (TIBCO® Statistica, Hamburg, Germany). To determine the relationship between the studied indicators and the biotype of the plant, soil type, and fertilization level, principal component analysis (PCA) was performed in the R program (version 3.6.1). The *ggfortify* package (version 0.4.9) presented the analysis results as a biplot chart (Tang *et al.* 2016).

Results

The competitiveness of bentgrass toward winter wheat in the 2018/2019 season

The analysis of the competitiveness indicators in the 2018/2019 season showed varied competitiveness, depending on the wheat characteristics tested and the research variant used: bentgrass biotype, soil type, and fertilization level.

The crop characteristics impacted by the bentgrass (Kcu index) in the 2018/2019 season showed, in most cases, a negative impact of bentgrass on winter wheat, as evidenced by the positive values of this index (Table 2). The exceptions are negative values, i.e., the stimulating effect of the sensitive biotype of bentgrass on wheat stem length (–2.10%) on the non-fertilized clay soil. Additionally, the lack of competition between wheat and sensitive bentgrass (0%) was indicated by the number of stem internodes in clay soil, regardless of fertilization. For the control, the indices took the value of 0 due to the lack of relative competition between plants (the control consisted only of winter wheat plants).

The values of the indicator of wheat displacement by bentgrass (Kwu) showed that in all tested variants, the weed harmed the number of winter wheat stems (Table 3). Similar results were obtained in the analysis of the indicator of wheat productivity by bentgrass (Kou). Bentgrass harmed the grain yield of wheat, the weight of one ear, the biomass of the plant, and the root biomass (Table 3). The slightly stimulating effect of bentgrass on wheat thousand-grain mass was noted only for AB-resistant bentgrass on fertilized clay soil and sensitive bentgrass on non-fertilized sandy soil, which was –0.78% and –1.80%, respectively. The productivity of winter wheat index, such as biomass of one plant and root biomass Kou, were affected most by the resistant biotype B2 regardless of the soil and the fertilization level (Table 3).

The assignment of individual treatments to individual clusters in the 2018/2019 season is presented in the dendrogram in Figure 1. Three clusters were distinguished in the analyzed season. One of the separate clusters was the control (weed-free wheat K-PZ), which resulted directly from the calculating method adopted in the methodology. It was assumed that the control had indicators equal to 0%. In the remaining branches, there were two main clusters. One of them (the lowest branch) consisted almost exclusively of objects with the B1-resistant biotype of bentgrass and wheat on clay or sandy soil, regardless of fertilization. This cluster also included the B2 biotype on fertilized clay soil. The second branch included three clusters. They contained other resistant and sensitive bentgrass biotypes. It should also be noted that the AB biotype often showed high similarity to the sensitive biotypes S1 and S2, especially when the same type of soil substrate and/or the same fertilization level were used.

The first component (PC1) explained nearly 62% of the variability (Fig. 2). The greatest influence on this component was the number of grains per plant, grain yield per plant, mass of one ear, biomass of plant, and root biomass, i.e., indicators related to the number and yield of grains, as well as the mass of the ear and the biomass of the plant. The second component (PC2) explained nearly 15% of the variability (Fig. 2). The variables with the greatest impact on PC2 were the stem length and the internode number.

Analysis of the biplot (Fig. 2) indicated the existence of a significant positive correlation between the stem length (DP) and the number of internodes (LMZ), the weight of one ear (MJK) and the number of grains per plant (LZ), the number of ears per plant (LKR) and the number of stems per plant (LZZ). The location of the vectors may suggest the existence of a weaker correlation between the length of the ear (DD) and the grain

Table 2. Index of wheat characteristics impacted by silky bentgrass (Kcu) in the 2018/2019 season

Bentgrass biotype	Soil	Fertilization	Kcu [%]											
			number ears per plant LKR		stem length DP		internodes number LMZ		ear length DK		number grains per ear LZK		number grains per plant LZ	
			mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.
S1	S	a0	29.41	5.88	21.00	12.34	23.08	13.32	5.62	11.46	7.02	16.08	33.19	16.22
S1	S	a1	16.36	5.14	12.06	12.34	13.33	18.86	13.75	13.73	25.00	22.50	36.13	21.73
S1	C	a0	18.52	4.58	1.97	5.44	0.00	12.37	13.55	21.69	10.84	29.22	27.97	22.50
S1	C	a1	25.33	13.60	8.33	6.98	6.67	9.43	8.33	12.27	12.87	19.60	32.73	25.54
S2	S	a0	15.69	14.80	8.48	7.25	15.38	13.32	18.13	10.99	42.11	13.93	51.77	7.70
S2	S	a1	21.82	11.35	5.18	8.53	6.67	11.55	20.42	11.34	33.82	15.91	46.94	18.38
S2	C	a0	31.82	4.55	–2.10	12.98	0.00	12.37	10.36	18.40	12.05	28.08	39.76	22.76
S2	C	a1	26.67	11.55	1.34	8.18	0.00	0.00	13.14	13.95	23.76	22.29	44.33	19.57
B1	S	a0	31.37	12.25	23.99	15.90	23.08	13.32	29.38	5.73	54.39	13.25	67.95	11.51
B1	S	a1	34.55	5.45	21.97	14.49	26.67	11.55	27.50	11.92	45.59	15.49	64.52	8.46
B1	C	a0	27.27	12.03	21.04	8.19	21.43	12.37	30.68	11.40	36.14	16.30	53.98	12.57
B1	C	a1	40.00	10.58	17.72	8.62	20.00	20.00	22.12	18.57	22.77	27.22	55.47	9.46
B2	S	a0	25.49	3.40	10.98	14.19	15.38	13.32	25.00	11.25	38.60	16.08	54.07	9.91
B2	S	a1	20.99	4.58	7.34	7.86	6.67	11.55	16.25	24.40	26.47	39.79	40.50	35.36
B2	C	a0	33.33	2.62	16.88	11.07	14.29	21.43	17.53	19.57	15.66	28.99	44.12	19.63
B2	C	a1	20.00	12.00	10.20	7.45	6.67	11.55	17.31	6.00	37.62	16.54	51.56	6.57
AB	S	a0	27.45	12.25	14.77	8.32	23.08	13.32	8.75	23.14	15.79	37.95	35.07	36.42
AB	S	a1	25.45	11.35	13.30	13.71	20.00	20.00	15.00	16.25	32.35	30.99	51.13	19.23
AB	C	a0	27.27	15.75	9.47	13.18	7.14	12.37	12.75	9.33	25.30	29.22	45.53	23.72
AB	C	a1	13.33	9.24	5.39	8.87	6.67	11.55	14.74	14.08	25.74	19.48	36.79	12.29

Legend: S1, S2 – susceptible biotypes, B1, B2 – single herbicide resistant biotypes, AB – cross-resistant biotype, S – sandy soil, C – clay soil, a0 – non-fertilized, a1 – N fertilized, S.D.– standard deviation

Table 3. Index of wheat displacement by bentgrass (Kwu) and index of wheat productivity impacted by bentgrass (Kou) in the 2018/2019 season

Bentgrass biotype	Soil	Fertilization	Kwu [%]		Kou [%]									
			number stems per plant LZZ		mass grains per plant PZ		thousand-grains mass MTZ		ear mass MJK		plant biomass BR		root biomass BK	
			mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.
S1	S	a0	29.41	5.88	63.75	5.86	44.05	19.11	57.63	16.79	51.91	6.40	57.47	12.11
S1	S	a1	16.36	5.14	42.93	25.54	12.22	25.79	40.81	23.78	38.19	12.47	42.84	16.90
S1	C	a0	18.52	4.58	40.47	27.10	19.77	17.07	40.30	33.55	29.54	7.84	32.50	10.39
S1	C	a1	25.33	13.60	38.57	25.64	12.60	11.54	37.43	25.41	38.00	16.77	58.00	10.99
S2	S	a0	16.12	14.11	48.00	26.56	-1.80	40.55	45.29	19.87	38.19	12.03	36.26	13.89
S2	S	a1	21.82	11.35	55.46	32.70	24.16	38.23	57.32	27.00	44.64	15.44	47.05	19.72
S2	C	a0	31.82	4.55	40.51	35.36	5.19	19.40	38.82	33.79	30.61	19.59	36.51	20.67
S2	C	a1	26.67	11.55	51.88	28.03	19.29	20.14	53.50	24.46	48.08	9.69	48.56	25.89
B1	S	a0	31.37	12.25	79.71	13.24	38.57	26.79	81.28	3.41	66.99	3.36	74.31	3.33
B1	S	a1	34.55	5.45	78.89	12.63	45.80	26.45	77.57	13.44	67.82	11.38	72.69	14.37
B1	C	a0	27.27	12.03	72.55	1.24	35.73	22.79	70.11	2.28	66.03	8.38	72.47	5.44
B1	C	a1	40.00	10.58	69.17	2.64	30.51	12.49	66.48	5.74	67.55	8.65	74.26	7.84
B2	S	a0	25.49	3.40	64.69	17.63	23.52	39.03	59.61	28.34	41.96	7.74	49.50	5.46
B2	S	a1	20.99	4.58	53.65	19.73	16.25	24.92	52.73	26.06	38.77	5.61	48.26	5.60
B2	C	a0	33.33	2.62	52.22	29.20	14.59	33.96	54.58	26.37	58.82	10.43	69.74	7.65
B2	C	a1	20.00	12.00	75.92	11.43	48.53	31.33	77.53	8.49	54.88	19.32	67.11	10.14
AB	S	a0	27.45	12.25	49.49	26.93	19.71	17.43	42.18	16.63	38.67	11.81	42.12	21.86
AB	S	a1	25.45	11.35	59.37	6.59	13.87	20.35	57.43	6.82	37.53	16.58	52.28	14.50
AB	C	a0	27.27	15.75	47.99	18.54	-0.78	18.81	47.72	20.20	54.63	12.60	66.85	10.18
AB	C	a1	13.33	9.24	52.44	18.94	26.42	22.43	57.91	15.07	31.69	16.96	39.58	33.09

Legend: S1, S2 – susceptible biotypes, B1, B2 – single herbicide resistant biotypes, AB – cross-resistant biotype, S – sandy soil, C – clay soil, a0 – non-fertilized, a1 – N fertilized, S.D.– standard deviation

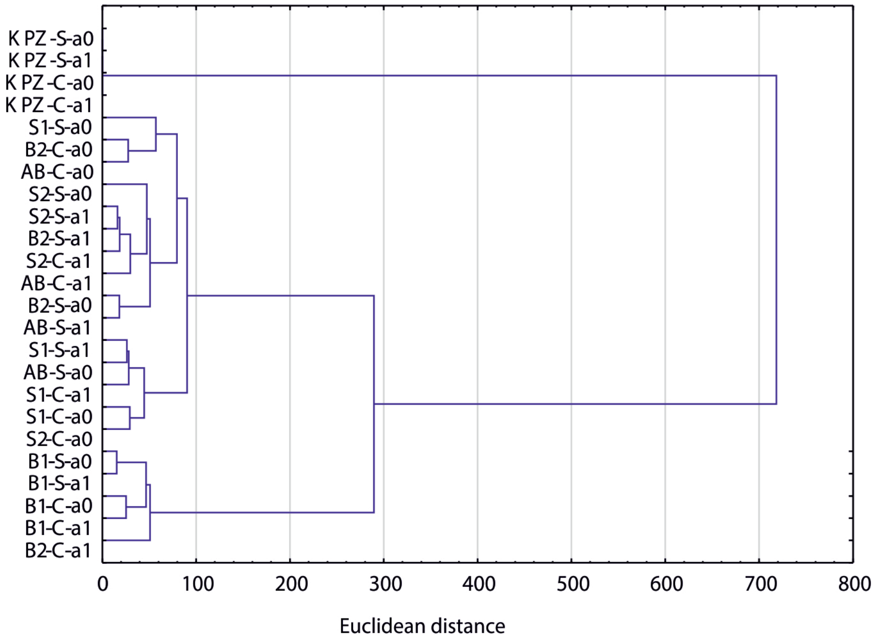

Fig. 1. Groups of the analyzed treatments in the 2018/2019 season, considering all competitiveness indicators, based on the cluster analysis
Legend: K PZ – control – winter wheat only; S1, S2 – sensitive biotypes; B1, B2 – biotypes with single resistance; AB – biotype with multiple-resistance; S – sandy soil; C – clay soil; a0 – no N fertilization; a1 – N fertilized

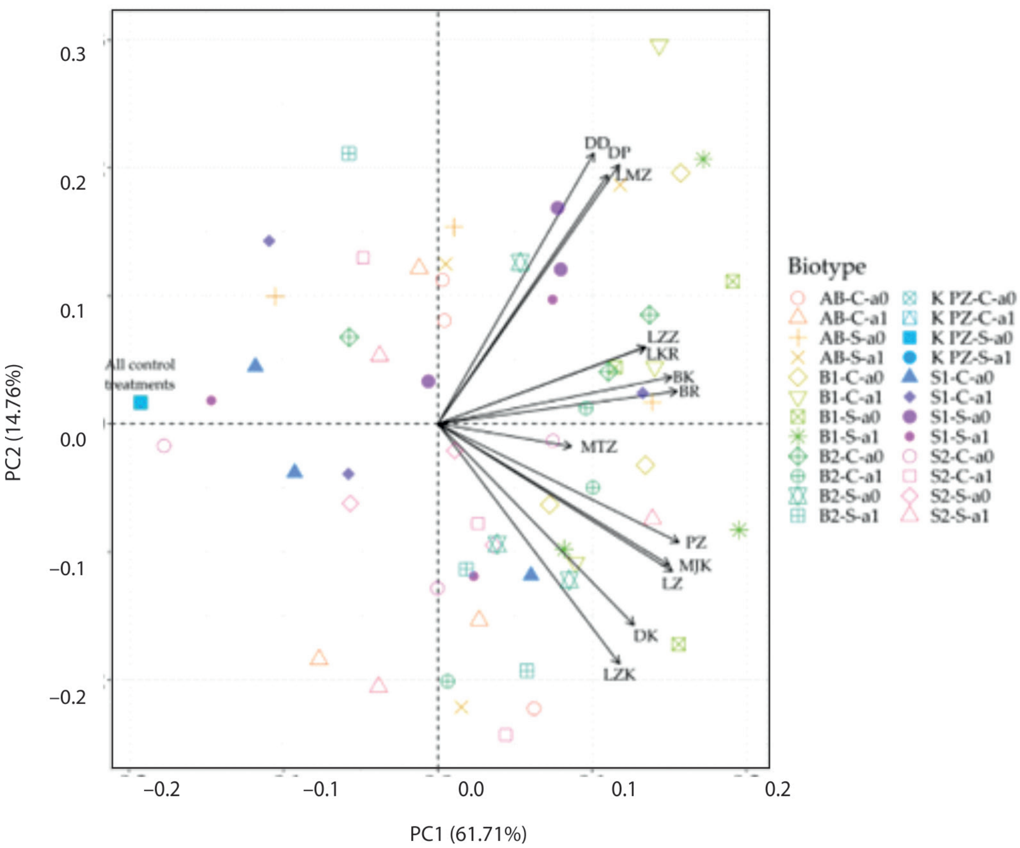

Fig. 2. Principal Component Analysis (PCA) biplot shows the relationship between competitiveness indicators calculated for the winter wheat, in competition with the bentgrass biotype of different herbicide resistance in two different soil types, and fertilization levels in the 2018/2019 season
Legend: PC1 – first component; PC2 – second component; LZZ – number of stems per plant; LKR – number of ears per plant; DP – stem length; LMZ – number of stem internodes; DD – stem length; DK – ear length; LZK – number grains per ear; LZ – number of grains per plant; PZ – grain mass one plant; MTZ – mass of a thousand grains; MJK – mass of one ear; BR – biomass of one plant, BK – root biomass

yield per plant (PZ), the number of stem internodes (LMZ) and stem length (DP), and the weight of one ear (MJK) and the number of grains per plant (LZ). Analysis of the chart also provides information about the relationship between the biotype x soil x fertilization level and the measured indicator. Both the resistant biotype AB in the variant with clay and sandy soil, without and with fertilization, as well as the sensitive biotype in light soil without fertilization, were associated with higher values of the indicators of stem length (DP) and the number of stem internodes (LMZ). In turn, the number of ears per plant (LKR), the number of stems per plant (LZZ), root biomass (BK), and the biomass of one plant (BR) were mainly associated with the resistant biotype B2. The resistant biotype B1 in the sandy soil variant showed a greater relationship with the grain yield per plant (PZ), the weight of one ear (MJK), and the number of grains per plant (LZ). The indicators of ear length (DK) and number of grains per ear (LZK) were mainly related to the resistant biotype B2 and the sensitive biotype on sandy soil.

The competitiveness of bentgrass toward winter wheat in the 2019/2020 season

The analysis of the weed impact index on the characteristics of the crop (Kcu) in the 2019/2020 season showed that in most of the tested variants, bentgrass harmed winter wheat (Table 4). The Kcu index value of 0% for the number of ears on the plant indicated a lack of competition between the crop plant and the S1 biotype. On the other hand, a Kcu index value of 25 indicated an unfavorable impact of the S1 biotype on the number of grains in the ear of winter wheat. The exception was the stimulating effect of the sensitive biotype (S2). This situation concerned parameters such as the ear length on the non-fertilized sandy soil (Kcu –0.98%) and the ear length on the non-fertilized clay soil (Kcu –7.98%). No competition was observed for the number of ears per plant between wheat and sensitive and AB-resistant bentgrass on the fertilized and non-fertilized sandy soil and the number of internodes for the sensitive and B2 biotypes on fertilized clay soil.

The Kwu index is an indicator of the displacement of the crop by weeds. The values of the indicator of crop displacement (Kwu) showed that in most of the tested variants, the bentgrass harmed the crop (Table 5). No competition between wheat and bentgrass was found only for sensitive and AB-resistant biotypes on non-fertilized or fertilized sandy soil. Also, a value of 0% meant no reduction in the number of winter wheat stalks under the influence of cereal broom biotype S1. Analysis of the indicator of crop productivity impacted by bentgrass (Kou) also confirmed the negative impact of bentgrass on the grain yield per wheat plant, the weight of one ear, the biomass of the plant, and the biomass of wheat roots, regardless of the tested variants (Table 5). A stimulating effect on wheat thousand-grain mass was observed only by the sensitive biotypes on sandy and clay soils. The Kou index value in these cases was –1.87% and –3.56%, respectively.

Summing up the analysis of competitiveness indicators in the 2019/2020 season, the greatest adverse impact on the morphology and yield of winter wheat was displayed by the resistant bentgrass biotype B2 on fertilized clay soil. In this case, the highest Kcu, Kwu, and Kou indices values were obtained for most crop parameters, except for the stem length and the number of stem internodes. If the values of the Kcu (for the parameter number of ears per plant) and Kwu (number of stems per plant) are the same, all wheat stems are ear-bearing.

The assignment of individual variants to appropriate clusters in the 2019/2020 season is presented in the dendrogram in Figure 3. Two clusters were distinguished in the analyzed season. Next to the control objects, the first branch comprised sensitive bentgrass biotypes S1 and S2 on both soil types and fertilization levels. Biotype AB on sandy fertilized soil and unfertilized clay soil was similar to sensitive biotypes. Within the second cluster, the similarity of the sensitive biotypes S1 and S2 (tested on a heavy soil substrate, fertilized) with the resistant biotype B2 (tested on a heavy soil substrate, with and without fertilization) and the resistant AB biotype (on sandy unfertilized soil). A separate branch within this cluster included all variants with the B1 biotype.

The first component (PC1) explained approximately 51% of the variability (Fig. 4). By far, the greatest influence on this component was the competitiveness indicators related to the length of the ear (DK), the number and yield of grains (LZ and PZ), as well as the weight of one ear (MJK) and root biomass (BK). The second component (PC2) explained nearly 17% of the variability (Fig. 4). The variables with the greatest impact on PC2 were primarily stem length (DP) and the number of internodes (LMZ), i.e., related to the spike and stem morphological characteristics. Analysis of the biplot (Figure 4) indicated the existence of a significant positive correlation (parallel vectors) between the number of grains per ear (LZK) and root biomass (BK), between the grain yield of one plant (PZ), the weight of one ear (MJK) and the number of grains per plant (LZ), and the number of ears (LKR) and the number of stems per plant (LZZ). It can also be noted that there was a weaker correlation between resistant biotypes B1 and B2 on light soil in both fertilization variants and the number of internodes (LMZ) and the grain yield per plant (PZ), the number of grains per plant (LZ), and the weight of one ear (MJK). In turn, the sensitive biotype S2 was particularly associated

Table 4. Index of wheat characteristics impacted by silky bentgrass (Kcu) in the 2019/2020 season

Bentgrass biotype	Soil	Fertilization	Kcu [%]											
			number ears per plant LKR		stem lenght DP		internodes number LMZ		ear length DK		number grains per ear LZK		number grains per plant LZ	
			mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.
S1	S	a0	0.00	6.67	1.17	9.90	7.69	23.08	14.08	23.75	25.00	37.50	21.37	43.61
S1	S	a1	4.55	23.62	4.94	10.68	6.67	11.55	10.81	16.38	11.69	23.81	17.93	18.21
S1	C	a0	12.85	11.92	3.57	9.84	6.67	11.55	9.77	11.94	13.48	15.57	24.79	23.99
S1	C	a1	37.84	4.68	5.44	9.37	0.00	0.00	16.72	8.38	10.48	11.90	44.35	3.28
S2	S	a0	2.22	7.70	3.94	13.56	7.69	23.08	2.82	34.00	12.50	43.75	12.25	42.45
S2	S	a1	0.00	3.94	12.93	8.39	20.00	20.00	14.86	20.80	23.38	27.64	22.93	28.13
S2	C	a0	11.76	10.19	6.05	12.27	13.33	11.55	-7.89	20.96	7.87	25.52	19.48	27.72
S2	C	a1	33.78	2.34	8.52	3.82	0.00	0.00	21.98	18.13	22.86	24.41	48.27	17.90
B1	S	a0	15.56	3.85	17.99	8.60	30.77	0.00	24.65	14.99	39.58	28.18	47.01	26.16
B1	S	a1	15.91	10.41	23.05	10.74	33.33	11.55	31.98	15.07	38.96	25.05	49.42	16.27
B1	C	a0	29.41	15.56	21.30	9.65	33.33	11.55	16.92	17.48	28.09	16.97	51.56	6.59
B1	C	a1	48.65	2.34	18.83	9.01	20.00	20.00	35.29	13.15	40.00	18.74	69.26	8.23
B2	S	a0	13.33	6.67	8.36	15.58	15.38	26.65	9.15	30.47	18.75	45.07	28.35	39.65
B2	S	a1	18.18	13.64	19.37	17.85	26.67	23.09	25.68	14.62	31.17	17.57	41.66	23.82
B2	C	a0	23.53	0.00	2.67	8.47	6.67	11.55	1.13	23.93	22.47	30.89	41.75	23.21
B2	C	a1	44.59	9.36	1.34	11.52	0.00	0.00	22.91	11.15	20.00	13.09	54.76	13.58
AB	S	a0	22.22	13.88	12.24	19.16	15.38	26.65	9.86	19.63	37.50	22.53	48.29	27.90
AB	S	a1	0.00	3.94	4.99	7.54	13.33	11.55	24.32	8.86	38.96	8.11	38.36	9.98
AB	C	a0	11.76	5.88	12.48	17.36	20.00	20.00	13.16	12.56	22.47	16.85	33.44	10.15
AB	C	a1	44.59	8.44	12.90	8.52	6.67	11.55	27.86	13.18	28.57	18.74	59.11	17.01

Legend: S1, S2 – susceptible biotypes, B1, B2 – single herbicide resistant biotypes, AB – cross-resistant biotype, S – sandy soil, C – clay soil, a0 – non-fertilized, a1 – N fertilized, S.D.– standard deviation

Table 5. Index of wheat displacement by bentgrass (Kwu) and index of wheat productivity impacted by bentgrass (Kou) in the 2019/2020 season

Bentgrass biotype	Soil	Fertilization	Kwu [%]		K_{ou} [%]									
			number stems per plant LZZ		mass grains per plant PZ		thousand-grains mass MTZ		ear mass MJK		plant biomass BR		root biomass BK	
			mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.
S1	S	a0	0.00	6.67	50.98	33.84	36.46	38.64	51.16	30.26	24.88	7.60	13.80	4.52
S1	S	a1	4.55	23.62	13.97	25.35	-3.56	16.39	16.61	16.51	28.39	34.60	22.53	26.23
S1	C	a0	12.85	11.92	22.34	30.05	-1.87	39.07	29.26	23.53	32.90	14.46	31.68	20.36
S1	C	a1	37.84	4.68	45.93	23.13	5.06	39.06	49.17	22.63	48.21	3.92	55.98	12.50
S2	S	a0	2.22	7.70	27.79	42.49	20.69	11.01	16.62	55.16	37.09	19.99	28.15	7.75
S2	S	a1	0.00	3.94	34.70	15.79	13.01	12.45	39.03	14.85	40.96	13.80	42.28	3.10
S2	C	a0	11.76	10.19	29.57	32.41	15.46	32.49	35.20	31.87	20.87	21.40	25.71	21.42
S2	C	a1	33.78	2.34	57.12	26.11	20.32	27.45	55.73	24.74	52.38	4.95	50.23	33.61
B1	S	a0	15.56	3.85	69.17	29.40	51.14	28.80	66.15	34.75	62.66	5.67	61.52	1.93
B1	S	a1	15.91	10.41	67.91	11.84	36.78	17.91	67.31	9.78	65.04	3.83	65.51	5.37
B1	C	a0	29.41	15.56	75.07	10.41	49.34	22.57	71.64	11.42	73.58	2.79	72.00	2.85
B1	C	a1	48.65	2.34	86.19	4.41	54.77	13.84	86.47	4.09	77.95	5.56	74.66	9.78
B2	S	a0	13.33	6.67	39.52	26.71	12.78	23.36	36.11	29.93	24.59	21.77	26.99	32.85
B2	S	a1	18.18	13.64	44.16	34.47	10.42	20.33	45.23	31.62	48.83	16.57	60.83	2.99
B2	C	a0	23.53	0.00	53.38	26.08	21.39	32.88	51.70	29.22	55.98	37.79	53.11	14.48
B2	C	a1	44.59	9.36	60.75	26.96	17.16	51.56	62.39	22.45	63.03	14.94	63.56	16.56
AB	S	a0	22.22	13.88	63.79	33.45	39.44	26.23	54.65	46.81	1.79	1.54	48.10	22.94
AB	S	a1	0.00	3.94	52.36	15.34	23.20	22.15	56.98	16.66	21.09	20.41	25.92	20.84
AB	C	a0	11.76	5.88	41.45	19.75	15.06	24.58	42.16	20.49	34.00	5.84	51.89	18.54
AB	C	a1	44.59	8.44	73.19	9.02	32.92	19.70	73.51	9.12	61.86	12.91	66.73	10.87

Legend: S1, S2 – susceptible biotypes, B1, B2 – single herbicide resistant biotypes, AB – cross-resistant biotype, S – sandy soil, C – clay soil, a0 – non-fertilized, a1 – N fertilized, S.D.– standard deviation

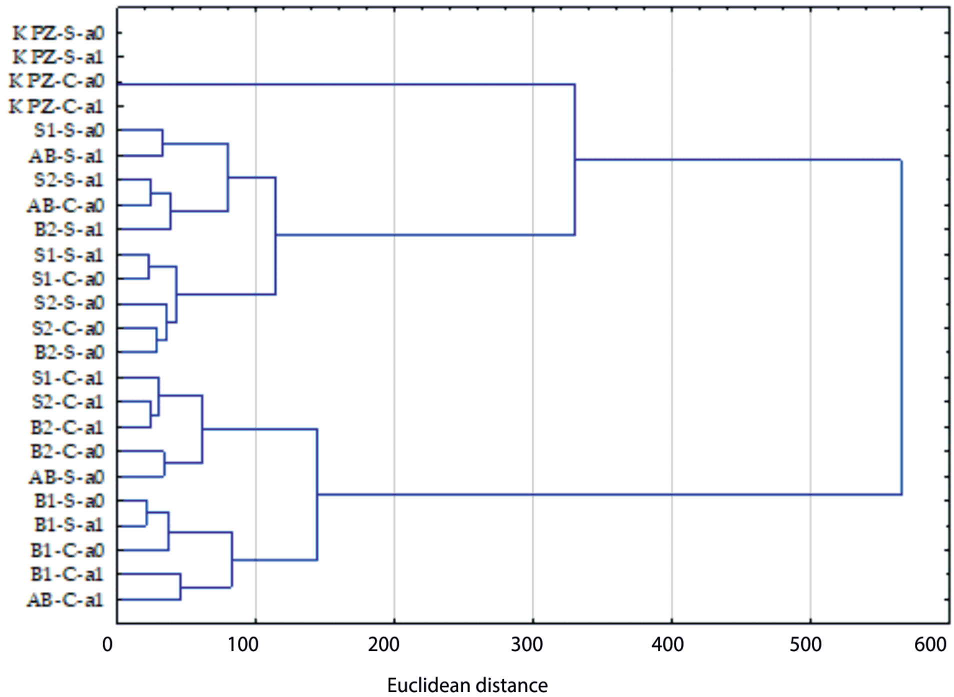

Fig. 3. Groups of the analyzed treatments in the 2019/2020 season, considering all competitiveness indicators, based on the cluster analysis
Legend: K PZ – control - winter wheat only, S1, S2 – sensitive biotypes, B1, B2 – biotypes with single resistance, AB – biotype with multiple-resistance, S – sandy soil, C – clay soil, a0 – no N fertilization, a1 – N fertilized

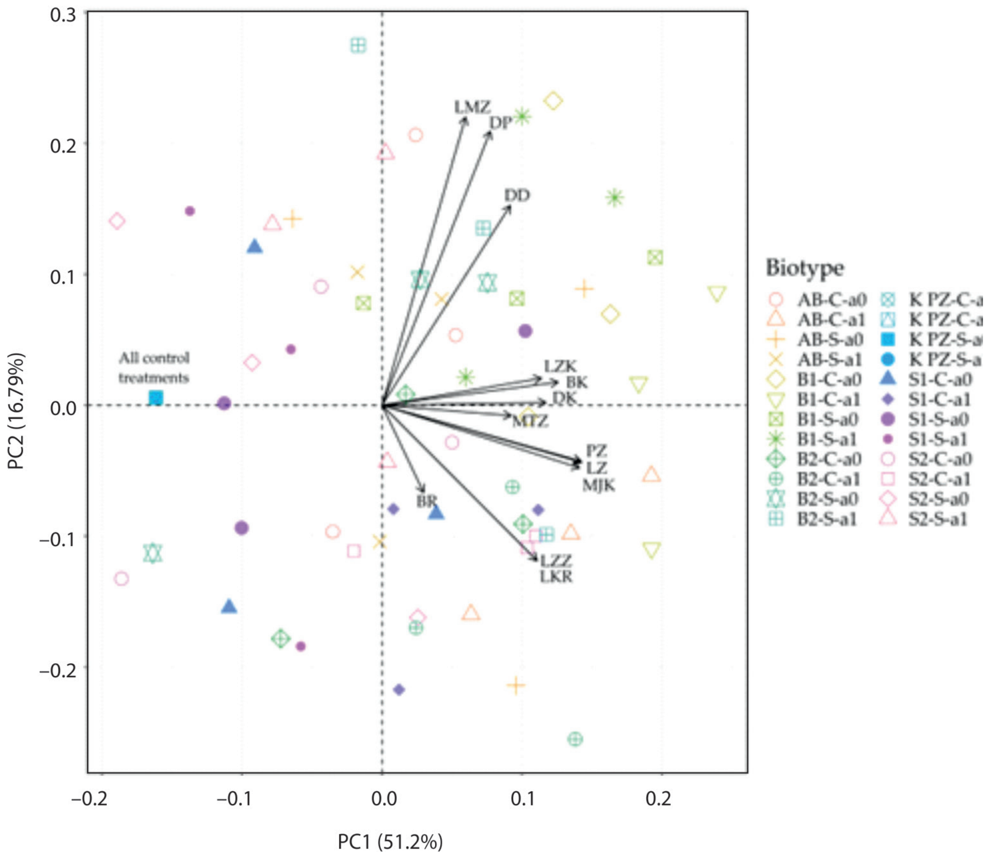

Fig. 4. Principal Component Analysis (PCA) biplot shows the relationship between competitiveness indicators calculated for the winter wheat, in competition with the bentgrass biotype of different herbicide resistance in two different soil types, and fertilization levels in the 2019/2020 season
Legend: PC1 – first component, PC2 – second component, LZZ – number of stems per plant, LKR – number of ears per plant, DP – stem length, LMZ – number of stem internodes, DD – stem length, DK – ear length, LZK – number grains per ear, LZ – number of grains per plant, PZ – grain yield from one plant, MTZ – mass of one thousand grains, MJK – mass of one ear

with the indicators of the number of ears (LKR) and the number of stems (LZ). The data obtained for the 2019/2020 growing season indicated a greater relationship between resistant bentgrass biotypes growing on light soil substrates, with and without fertilization, and indicators related to wheat stem. However, the sensitive bentgrass biotypes greatly impacted the number of wheat ears and stems per plant on both fertilized soil types.

Discussion

Based on the analysis of biometric parameters and yield, this research showed the competitiveness (additive model) of resistant and sensitive bentgrass biotypes concerning winter wheat cv. Arkadia. It was assessed in two types of soil and fertilizer conditions.

The analysis of competitiveness indicators showed variable levels of competitiveness of weed biotypes toward winter wheat during two seasons. The results obtained in the 2018/2019 season do not allow for clearly indicating a specific research factor (fertilization or soil type) that influenced the competitiveness of the tested biotypes of bentgrass with winter wheat. Regardless of the soil type and fertilization used, in the case of traits related to the productivity of winter wheat (biomass of one plant and root biomass), the highest Kou index values were obtained for the bentgrass biotype with resistance to pyroxsulam. An unfavorable effect on the morphology and yield of winter wheat by this bentgrass biotype was also found in the 2019/2020 season. Plants growing on fertilized clay soil had the highest values of Kcu, Kwu, and Kou indices for most of the parameters tested. Additionally, principal component analysis (PCA), especially for the 2019/2020 growing season, indicated a greater relationship between resistant bentgrass biotypes on sandy soil, with and without fertilization, and indicators related to stem length.

There are few research results in the literature regarding the competitiveness between winter wheat and resistant and susceptible *A. spica-venti* biotypes. With the evolution of herbicide resistance in weeds, attention began to be paid to the traits of weeds that survived the herbicide treatment. Literature reports show that weeds with a herbicide resistance gene exhibit lower viability and reduced values of ecophysiological indices (Leroux 1993; Baucom and Mauricio 2004). Resistant biotypes, compared to sensitive ones, may have lower photosynthetic efficiency, lower LAI (Leaf Area Index), lower growth, lower biomass increase (accumulation), or be characterized by lower reproductive potential (Frenkel *et al.* 2017; Cousens and Fournier-Level 2018; Vila-Aiub 2019). This may suggest that resistant biotypes are less competitive with sensitive biotypes or the crop. However, the present studies did not confirm this statement. A competitive effect of susceptible bentgrass biotype on winter wheat was not seen. In some treatments, there was no or only negligible competition between wheat and susceptible biotypes. In contrast, in others, the presence of susceptible biotypes stimulated the parameters of winter wheat that were analyzed. This result suggests that the resistant biotype was more competitive with winter wheat than the susceptible one.

Based on a target-neighborhood design model, research by Babineau *et al.* (2017) did not indicate any significant competition between *A. spica-venti* biotypes resistant to ALS inhibitors and winter wheat. Costa and Rizzardi (2015) found that *Raphanus raphanistrum* biotypes sensitive or resistant to herbicides from the ALS inhibitor group significantly compete with winter wheat. In these studies, the resistant and susceptible biotypes significantly reduced the dry weight of wheat shoots, and interspecific competition was stronger for the sensitive biotype. The above results are consistent with the reports of Wandscheer *et al.* (2013) who observed interspecific competition of maize with *Eleusine indica*, where the dry matter value of maize decreased as the weed-to-crop ratio increased. Rigoli *et al.* (2008), who tested competition between winter wheat and *Raphanus raphanistrum*, observed that regardless of the tested biotype, the weed was more competitive with the crop when they occurred in the same ecological niche. In competition tests between soybean plants and *Raphanus sativus*, it was observed that the tested weed biotypes also have a higher competitive ability than the crop plant (Bianchi *et al.* 2006; Fleck *et al.* 2006; Bianchi *et al.* 2011). Gallon *et al.* (2015) showed that *Lolium multiflorum* biotypes significantly compete for environmental resources with barley. In turn, the experiments of Oliveira *et al.* (2014) indicate that soybeans have the same competitive ability as glyphosate-sensitive *Lolium rigidum* biotypes but are subject to competitive pressure from sensitive biotypes.

According to general ecological theories, herbicide-resistant weed biotypes are predicted to incur a cost of acquiring resistance (fitness cost) without herbicide application (Vila-Aiub *et al.* 2009). Under optimal growth conditions and without herbicide pressure or other stress factors, sensitive biotypes should ultimately dominate over resistant biotypes. For this reason, it can be assumed that in competition with a crop plant, sensitive biotypes will be more aggressive than resistant biotypes. However, acquiring an herbicide-resistant gene is not always associated with a fitness cost (Ghanizadeh and Harrington 2019). The present research showed that the appearance of an additional factor (soil type and fertilizer conditions) was not always associated with fitness costs in resistant biotypes.

This may increase the durability of resistant individuals in the biocenosis and their increased competition towards crop plants, as indicated by Ashigh and Tardif (2011) and Ghanizadeh and Harrington (2019).

In summary, the analysis of competitiveness indices did not show a clear effect of the soil type (clay or sandy soil) and fertilization on the competitiveness of different biotypes of bentgrass with winter wheat. The data obtained from the study suggest that the most adverse effect on the morphology and yield of winter wheat was the pyroxsulam-resistant biotype. In the 2018/2019 season, the highest values of the competitiveness index were obtained for this biotype for traits related to the biomass of wheat and root biomass, regardless of the soil type and the fertilization level. In the second season (2019/2020), the greatest adverse effect of this biotype was also confirmed for most of the winter wheat parameters tested on clay, fertilized soil. Principal component analysis (PCA), especially for the growing season 2019/2020, indicated a greater relationship between resistant bentgrass biotypes on sandy soil, with and without fertilization, and indicators related to stem length of winter wheat. Different numbers of biotypes of bentgrass and assessing their competitiveness on different varieties of winter wheat will allow for a broader look at the mutual interactions of plants. The results of interspecific competition may be useful in planning herbicide treatments consistent with site-specific weed management (SSWM). As shown by the research of Hamouz *et al.* (2014) on the assessment of spatial stability of weeds, weeding the entire plantation compared to SSWM does not significantly affect the changes in the number of weeds in individual years, which supports the use of the SSWM method. The research results on interspecific competitiveness (apart from the economic thresholds) may prove useful in planning precise treatments and, as a result, will allow for more economical use of herbicides.

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