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Environmental Factors Effects on Winter Wheat Competition with Herbicide-Resistant or Susceptible Silky Bentgrass (*Apera spica-venti* L.) in Poland

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Abstract: Environmental factors, including weather and soil conditions, can affect the competitive effects of weeds on crops. This work aimed at a comparison of the competitive abilities of winter wheat toward bentgrass (*Apera spica-venti* (L.) P. Beauv) with single herbicide resistance, multiple herbicide resistance, or a susceptible biotype in different environmental conditions of Poland. A replacement series competition model was applied in field conditions in 2017–2018 and 2018–2019 across the country. A competitive ratio (CR) was calculated for the relative biomass of plants and grain number. A canonical variate analysis (CVA) was performed for biological parameters and a day-difference in emergence between winter wheat and bentgrass with the hydrothermal coefficient and soil texture in all of the sites in each season separately. Winter wheat emergence was correlated with the amount of precipitation after seeding, and was fastest for five days in humid conditions, and slowest up to 22 days, when the precipitation in October was low. The CVA proved that winter wheat's competitive effects toward the susceptible or herbicide-resistant biotypes of bentgrass are site-specific. During the dry season, the bentgrass biotype with multiple herbicide resistance was more competitive toward winter wheat than the susceptible one. The wheat CR < 1 with regard to biomass and both biomass and the grain number was in 64% and 50% of all the combinations with the resistant biotype. In conclusion, weather affects the competitive effects of winter wheat toward herbicide-susceptible or resistant bentgrass.

Keywords: replacement series model; competitive ratio; environmental factors

1. Introduction

Weeds are the most important biotic factor affecting crop production, especially in organic farming and low-input agriculture [1]. Preventing weed-induced yield losses in

wheat has high significance for world food sustainability [2]. Environmental factors, including weather and soil conditions, are important factors influencing the yield of crops [3,4] and affecting the competitive effects of weeds on crops [5,6]. Lemerle et al. [7], in the studies on the competitive effects of 12 wheat varieties against *Lolium rigidum* (Gaud.) performed at several sites in southeastern Australia, found that the variety $\times$ environment effects affect largely variation in crop grain yield, which is also, to a smaller extent, attributed to variety $\times$ weed $\times$ environment effects. In other studies, it was shown that wheat was more competitive toward two dicotyledonous weeds, *Papaver rhoeas* (L.) and *Viola arvensis* (Murray), during the summer drought, which restricted late weed growth and competition [8].

One of the most important annual grass weeds of winter wheat in Central, Eastern, and Northern Europe is silky bentgrass or bentgrass (*Apera spica-venti* (L.) P. Beauv) [9–14]. The susceptible biotypes of bentgrass pose a significant competitive threat to crops, especially winter wheat [15]. A significant decrease in wheat yield is observed at a density of bentgrass panicles > 100 per m^2 [16]. Due to a high degree of morphological and genetic variation [17], bentgrass adapts quickly to changing agricultural landscapes [18], which leads to a fast selection of herbicide-resistant biotypes [19]. A logistic regression model performed across Europe revealed that crop rotation dominated by winter crops and conventional soil tillage significantly increases the probability of resistance selection of bentgrass [20]. Presently, there are 18 cases of herbicide-resistant bentgrass in 11 different countries in Europe, with most cases from the Czech Republic, Germany, and Poland [21–23]. Biotypes of bentgrass are resistant to the inhibitors of acetolactate synthase (ALS), photosystem II, and acetyl coenzyme-A carboxylase (ACC-ase), displaying single resistance, cross-resistance, and multiple resistance patterns [21]. In Poland, the biotypes of *A. spica-venti* resistant to ALS inhibitors, mostly chlorsulfuron and iodosulfuron, are very common, especially in northern, western, and central parts of the country [24–26].

On the other hand, the weather and soil effects on winter wheat competitiveness against herbicide-resistant and -susceptible bentgrass are not known. The competitiveness of bentgrass increases when a set of factors occurs, i.e., lighter soil texture, cooler climate, and higher rainfall in the crop sequence comprising only autumn-sown crops and non-inversion tillage [27]. A recent study showed that in a target-neighborhood competition model for wheat and bentgrass, the populations of bentgrass did not display any differences in biometrical characteristics and, as a result, competitive effects toward wheat [18]. However, more so-called “fitness benefits” of non-target site-resistant biotypes of bentgrass were found, i.e., earlier germination and flowering, than susceptible ones. The authors propose that these findings could improve the management of herbicide-resistant biotypes of bentgrass [18].

In this work, a replacement series competition model [28] was applied to study winter wheat’s competitive abilities toward herbicide-resistant or -susceptible bentgrass across Poland. The method is suitable for studying the response of the yield to the proportion of competing plants. It also allows the yielding efficiency of plants in a mixture with monoculture to be determined [28,29]. However, the method also has limitations, i.e., it is not representative of most field situations where crops occur at a constant density, and the experimental outcomes may depend upon the total plant density selected and specific resource supply conditions used [30].

We hypothesize that environmental factors, i.e., weather conditions combined with soil texture, influence winter wheat’s competitive abilities toward herbicide-resistant and -susceptible biotypes of bentgrass. The work aimed to compare the competitive abilities of winter wheat toward bentgrass (*Apera spica-venti* (L.) P. Beauv) with single herbicide resistance to ALS inhibitors, multiple herbicide resistance to ALS and ACC-ase inhibitors, or a susceptible biotype in different environmental conditions of Poland.

2. Materials and Methods

In a replacement series competition model [29], two pot experiments in field conditions were set at seven different sites across Poland (Figure 1).

Figure 1. Distribution of the study sites. Lp—Lipnik; Mch—Mochelek; WG—Winna Góra; Cz—Czesławice; Sw—Swojczyce; Wr—Wrocław; Md—Mydlniki.

The experimental design was randomized blocks with three replications. The first experiment was performed in the 2017–2018 season in five different sites, and the second one in the 2018–2019 season in seven sites (Table 1). The scheme of pots and the distribution of plants in a pot was the same in every site. In each site, 36 pots (22 cm diameter, 7 L vol., 0.038 m² area) were dug into the soil at a 0.5 m distance, and ca. 2.5 cm of pot was above the soil surface. Next, they were filled up with a local arable soil from 0–30 cm layer. Before placing it in the pots, the soil was sieved through metal mesh to remove stones and other larger impurities. A soil sample was taken for detailed texture and chemical analyses (Table 1). The area between pots was laid with black foil, and the whole experiment was protected from birds with a fine plastic net.

Table 1. Sites of the experiments with their coordinates and soil characteristics.

Site	Latitude	Longitude	Particles (%)			Texture [31]	N ¹	P	K	OM	pH
			Sand	Silt	Clay						
Lipnik	53°34' N	14°95' E	85.4	14.0	0.6	Loamy sand	0.11	232	301	2.2	6.4
Mochelek	53°20' N	17°86' E	84.7	14.3	1.1	Loamy sand	0.17	238	296	2.6	6.6
Winna Góra	52°12' N	17°26' E	70.4	26.3	3.4	Sandy loam	–	137	162	1.1	5.5
Czesławice	51°18' N	22°16' E	15.8	72.6	11.6	Silt loam	0.12	158	196	1.5	6.4
Swojczyce	51°06' N	17°08' E	66.0	26.0	8.0	Sandy loam	0.51	128	125	1.23	6.5
Wrocław	51°04' N	17°02' E	56.0	23.0	21.0	Sandy clay loam	1.7	182	197	1.19	6.2
Mydlniki	50°07' N	19°84' E	39.0	52.0	9.0	Silt loam	0.07	173	196	1.14	6.3

¹ N—nitrogen (%), P—phosphorus (mg kg^{−1}), K—potassium (mg kg^{−1}), OM—organic matter (%).

The characteristics of both R (herbicide-resistant) and S (herbicide-susceptible) biotypes of silky bentgrass are presented in Table 2.

The same susceptible (S) and herbicide-resistant biotypes of bentgrass were used in all of the sites; however the biotype with a single resistance (RS) was used only in the 2017–2018 season and the biotype with a multiple resistance (RM) only in the 2018–2019 season. The competitive effects of each R biotype of bentgrass were tested against winter wheat (WW) cv. Arkadia (breeder: HR Danko PL).

Table 2. Characteristics of herbicide-susceptible (S) and -resistant (RS and RM) biotypes of silky bentgrass (*Apera spica-venti* (L.) P. Beauv) used in the pot experiments. Numbers in brackets relate to the effective dose of active ingredient causing a 50% of reduction in plant biomass (ED50).

Biotype	Herbicide (HRAC ¹ Group)			
	Fenoxaprop-P (HRAC A)	Pinoxaden (HRAC A)	Pirotolam (HRAC B)	Iodosulfuron (HRAC B)
RS	S ²	S	RRR ³ (86)	S
RM	RRR (>2650)	RRR (201)	RRR (>288)	RRR (>320)
S	S (13.2)	S (2.8)	S (<0.56)	S (2.41)

¹ HRAC—Herbicide Resistance Action Committee; ² S—susceptible; ³ RRR—highly herbicide-resistant.

Grains of WW and RS or RM, and WW and S were sown in ratios: WW10:R0, WW8:R2, WW6:R4, WW4:R6, WW2:R8, WW0:R10; WW10:S0, WW8:S2, WW6:S4, WW4:S6, WW2:S8, and WW0:S10. Grains of WW, RS or RM, and S biotypes were sown on the same day, optimal for WW (Table 3). A few grains of WW were sown per spot at 2 cm deep and bentgrass at 0.5 cm deep. The spot of sowing each plant was marked.

Table 3. Dates of winter wheat sowing and harvest.

Site	2017–2018 Season		2018–2019 Season	
	Sowing Date	Harvest Date	Sowing Date	Harvest Date
Lipnik	20 October 2017	16 July 2018	17 October 2018	10 July 2019
Mochelek	9 October 2017	10 July 2018	17 October 2018	3 July 2019
Winna Góra	–	–	8 October 2018	11 July 2019
Czesławice	12 October 2017	13 July 2018	10 October 2018	23 July 2019
Swojczyce	18 October 2017	16 July 2018	13 October 2018	17 July 2019
Wrocław	27 October 2017	24 July 2018	25 October 2018	18 July 2019
Mydlniki	–	–	4 October 2018	4 July 2019

In spring, the density of winter wheat (WW) and bentgrass (B) plants was thinned to one per spot. During spring, N fertilization was applied in 30.0 g NH₄NO₃ m^{−2}; 50% of the dose was applied at the beginning of vegetation, and the other dose at wheat shooting (BBCH 31–33). Wheat was harvested at a full-grain maturity (BBCH 97–99), whereas B was collected after panicles were developed but before grains were shed.

At harvest, a fresh mass of plants, both WW and B, was weighed. Plants of WW were measured with a ruler from the base of the shoots until the highest ear's tip. All grains per WW plant were counted, and their fresh mass was weighed. Based on three samples of 100 grains, the 1000-grain weight (TGW) of WW was calculated. For B, the number of grains per plant was calculated. For this, grains in two 0.01 g samples were counted, and then the mean number of grains was related to the weight of all grains per plant.

2.1. Weather Conditions

Weather data, i.e., precipitation and air temperature, were collected during the study from the nearest weather stations (Tables S1 and S2). The weather data for the months from WW sowing until harvesting, with the temperature > 0 °C, namely October–December 2017 and April–July 2018, October–November 2018, and April–July 2019, were used to compute the hydrothermal coefficient (K) [32] according to the following equation:

$$K = 10P/t \quad (1)$$

where P is the precipitation total and t is the sum of daily air temperature values.

The classification is K < 1.3 moderately dry seasons, 1.3–1.6 optimum, and >1.6 classified as humid season [33]. The calculated K values are presented in Table 4.

Table 4. Hydrothermal coefficient (K) calculated for the 2017–2018 and 2018–2019 seasons for the study sites.

Site	2017–2018	Classification	2018–2019	Classification
Lipnik	2.1	Humid	0.9	Dry
Mochełek	2.2	Humid	0.5	Dry
Winna Góra	–	–	0.8	Dry
Czesławice	2.6	Humid	1.2	Relatively dry
Swojczyce	1.5	Optimal	1.2	Relatively dry
Wrocław	1.2	Relatively dry	0.9	Dry
Mydlniki	–	–	2.6	Humid

2.2. Statistical Analysis

The analysis was performed for the replacement series experiment [29]. The relative yield (RY) and the total relative yield (TRY) for all the measured parameters of B and WW were calculated according to the following formulas:

$$RY_{WW} = (p) (WW_{mix}/WW_{mon}) \quad (2)$$

$$RY_B = (p - 1) (B_{mix}/B_{mon}) \quad (3)$$

$$TRY = RY_{WW} + RY_B \quad (4)$$

where RY_{WW} is the relative yield of the WW, RY_B is the relative yield of the B, p is the proportion of WW, WW_{mix} is a value of the WW parameter analyzed for the mixture, WW_{mon} is a value of the WW parameter analyzed for the monoculture, B_{mix} is a value of the B parameter analyzed for the mixture, B_{mon} is a value of the B parameter analyzed for the monoculture, and TRY is the total relative yield. The RY values for WW and B represent the mean value per single plant per pot.

Two parameters, namely fresh plant biomass and the number of grains per plant, were measured for both WW and B. That is why these parameters, calculated into RY and TRY, were presented as graphs and fitted into one of the five competition models according to [28]. The comparisons between empirical and theoretical competition models for the plants' biomass and the number of grains per plant were tested by t-test independently for each biotype, year, and site. If the RY was a straight line, it denoted no competition, a convex line showed a benefit to species, and a concave line showed a loss to species. If the TRY equaled 1 (straight line), there was a competition for the same resources between both species/biotypes. If the TRY was greater than 1 (convex), there was no competition because the demand did not exceed the resources. If TRY was less than 1 (concave), there was an antagonism that resulted in mutual loss to the species involved [34].

Moreover, the competitive ratio (CR), representing the comparative growth of WW compared to B [34], was calculated based on fresh plant biomass (CRb) and the number of grains (CRgn), according to the following formula:

$$CR = ((1 - p)/p)/(RY_{WW}/RY_B), \quad (5)$$

WW was more competitive toward B if $CR > 1$.

The normality of distribution of the observed traits (CRb and CRgn) was tested with Shapiro–Wilk's normality test to check whether the analysis of variance (ANOVA) met the assumption that the ANOVA model's residuals follow a normal distribution. The homogeneity of variance was tested using the Bartlett test. Multivariate normality and homogeneity of variance–covariance matrices were tested by Box's M test. Next, the effects of the main factors under study (site, the proportion of plants in the mixture, and biotype) and their interactions were estimated with a linear model for the three-way ANOVA for particular traits independently for 2017–2018 and 2018–2019. The relationships between the CRb and CRgn were assessed based on Pearson's correlation coefficients and tested with the t -test for all of the sites separately in 2017–2018 and 2018–2019.

Additional biometric parameters of WW in competition with RS or RM and S bentgrass in 2017–2018 and 2018–2019, separately, were also analyzed using the canonical variate analysis (CVA) [35,36]. The CVA was applied to present a multi-trait assessment of the similarity of the investigated treatments in a lower number of dimensions with the least possible loss of information. This enabled graphic illustration of the variation in the traits of all treatments under analysis. The *r*-Pearson's correlation coefficients were estimated between values of the first two canonical variates and values of original individual traits to determine the relative share of each original trait in the multivariate variation of the treatments. There were five WW parameters included in this analysis, expressed as RY, and calculated as a mean value from all the tested plant ratios: mean length and fresh biomass of plant, number of grains per plant, the grain yield per plant, and the 1000-grain weight. The number of days from sowing until WW emergence and the day difference between WW and B emergence was also included in the analysis. The environmental characteristics of the sites, namely the hydrothermal coefficient K and soil texture, were included as categorization variables.

The GenStat v. 18 statistical software package was used for all the analyses.

3. Results

The emergence of WW was noted 8–15 and 5–22 days after sowing in 2017 and 2018, respectively (Table 5). The fastest emergence of WW (5 days) was noted in Mydlniki in 2018, where the precipitation in October was highest (52.6 mm) among the sites, but accompanied by a cool air temperature (8.2 °C). On the other hand, the longest emergence time (20 and 22 days) was noted in Mochełek and Winna Góra in 2018, where the precipitation in October was low, 27.4 and 21.1 mm, respectively (Table S1). Despite the date of sowing both WW and B being the same, B emerged, on average, 1–4 days later than WW in most sites (Table 5). In 2018 in Swojczyce, B emerged seven days after WW. In Mochełek and Czesławice in 2018, both WW and B emerged on the same day. The exception was Winna Góra in 2018, where B emerged seven days earlier than WW.

Table 5. Dates of winter wheat and bentgrass emergence, and the number of days from wheat sowing until emergence.

Site	2017			2018		
	WW ¹	Days to WW Emergence	B ²	WW	Days to WW Emergence	B
Lp	28 October 2017	8	30 October 2017	25 October 2018	8	29 October 2018
Mch	24 October 2017	15	26 October 2017	2 November 2018	16	2 November 2018
WG	–	–	–	30 October 2018	22	23 October 2018
Cz	27 October 2017	15	28 October 2017	22 October 2018	12	22 October 2018
Sw	26 October 2017	8	29 October 2017	23 October 2018	10	30 October 2018
Wr	7 October 2017	11	Nov. 10 XI 2017	5 November 2018	20	8 November 2018
Md	–	–	–	9 October 2018	5	12 October 2018

¹ WW—winter wheat; ² B—bentgrass.

In 2017–2018, the WW competition was tested against the biomass of bentgrass with a single resistance to piroxulam (RS) or susceptible biotype (S) (Figure 2, Table S3). The results show that in Lipnik (for S and WW), Wrocław, and Mochełek, the competitive model III occurred, pointing to two-sided negative impacts of competition on WW and RS or S bentgrass biomass. However, model I was also noted in other sites (Lipnik for RS and WW, Czesławice for S and WW, and Swojczyce for each biotype and WW), which points to both bentgrass and WW not competing in terms of biomass accumulation.

The competitive relations between WW and RS or S biotype, expressed by the number of grains per plant (Figure 3, Table S4), displayed different patterns for plant biomass. In Lipnik, the grain production of each bentgrass and WW was not affected (model IV). On the contrary, in Czesławice the RS and S biotypes and in Wrocław only the RS biotype produced a lower number of grains compared to WW (model IIb). In the other sites

(Mochełek and Swojczyce) there was no competition for grain production between RS or S and WW (model I) (Figure 3).

Figure 2. The substitutive competition model for the relative biomass yield of winter wheat (WW) and bentgrass in the 2017–2018 season, classified according to the t-test and p -values < 0.05 . (a) Competition between WW and bentgrass with a single resistance to piroxulam (RS), and (b) competition between WW and herbicide-susceptible bentgrass (S). Legend: ○—WW; △—RS; ×—S; □—RS + WW (a) or S + WW (b).

Figure 3. The substitutive competition model for the relative number of grains per plant of winter wheat (WW) and bentgrass in the 2017–2018 season, classified according to the *t*-test and *p*-values < 0.05. (a) Competition between WW and bentgrass with a single resistance to piroxulam (RS), and (b) competition between WW and herbicide-susceptible bentgrass (S). Legend: ○—WW; △—RS; ×—S; □—RS + WW (a) or S + WW (b).

The competitive ratio (CR) index was measured for two parameters, i.e., biomass and grain number of WW and B, in the plant ratios of 6WW:4B and 4WW:6B. The site $\times$ proportion and site $\times$ proportion $\times$ biotype interactions were significant for both CR indexes (Table S5).

The CR_{gn} was significantly correlated with the CR_b in the 2017–2018 season ($r = 0.712$, $p < 0.001$) (Figure 4). The analysis revealed that WW's competitive effects were higher

in the grain number (CRgn) than in the biomass (CRb). Interestingly, the WW was less competitive only in Mochełek and toward the S biotype. However, the competition with RS affected the number of grains more at both WW proportions in the mixture, as the CRgn value was below 1 for both Mch 0.4 RS and Mch 0.6 RS. In all the other sites, WW was more competitive toward both bentgrass biotypes, with $CRgn > 1$. The 0.6 proportion of WW in the mixture affected the WW competitive ratio in relation mainly to RS in three sites, namely, Lipnik, Mochełek, and Swojczyce. On the other hand, in Czesławice (Cz) the site effect prevailed over the effects of the bentgrass biotype or WW proportion in the mixture, which was displayed in the graph by a visible cluster. What is interesting is that in Czesławice the competitive ratio calculated for the relative grain number (CRgn) was very similar, in a range 1.3–1.9, regardless of the studied combinations. In the case of outliers, i.e., Sw 0.4 RS and Wr 0.6 RS, it looked more like an accidental situation than the trend.

Figure 4. The distribution of sites × winter wheat proportion in the mixture × bentgrass biotypes for the competitive ratio indices calculated for the relative number of grains (CRgn) and relative biomass of plant (CRb) in 2017–2018. Legend: Lp—Lipnik, Mch—Mochełek, Cz—Czesławice, Sw—Swojczyce, Wr—Wrocław (sites of experiments); RS—bentgrass biotype with a single resistance; S—susceptible biotype.

The CVA was performed to find the similarities in RS's and S's competitive effects toward WW between different study sites in 2017–2018. The first canonical variable was significantly positively correlated with the number of WW grains and the days from sowing until WW emergence, and negatively with the WW grain yield. On the other hand, the second canonical variable was positively correlated with WW grain yield but negatively with the WW biomass (Table S6).

The two first canonical variables accounted for 94.25% of the total multi-variability between the individual combinations (Figure 5). The analysis revealed that WW in competition with both bentgrass biotypes displayed the best attributes in Lipnik (humid season and loamy sand soil). In Swojczyce (optimal season, sandy loam), Czesławice (humid season, silt loam), and Wrocław (relatively dry season and sandy clay loam soil), the resistant biotype RS was less competitive toward WW, compared to the S biotype in Swojczyce and Czesławice.

Figure 5. Distribution of five sites where the competition of winter wheat (WW) was tested against bentgrass with a single resistance to piroxulam (RS) or susceptible (S) in 2017–2018, based on five biological parameters of WW, in the space of the first two canonical variables (V1 and V2). Sites: Lp—Lipnik, Mch—Mochelek, Cz—Czesławice, Sw—Swojczyce, Wr—Wrocław. Subscript “r” denotes the competition of WW with RS and the subscript “s” with S.

In the 2018–2019 season, WW’s competitive effects were tested against bentgrass with a multiple herbicide resistance (RM) and the same susceptible biotype (S) as in the 2017–2018 season. Figure 6 shows the relative yields of fresh biomass of the competing plants, and the competition model was based on the *t*-test (Table S7). The resistant biotype of bentgrass (RM) turned out to be competitive against WW in three sites out of seven, where competition model IIa was found. Interestingly, in three other sites neither the RM biotype nor WW were affected by competition (model I). The competitive efforts of the susceptible biotype S were variable depending on the site.

A detailed analysis of the effect of competition between WW and BM or S on the grain number (Figure 7, Table S8) was different than that for plant biomass. In four out of seven sites, model I was confirmed for both BM and WW, and S and WW.

The ANOVA indicated a statistically significant influence of sites and bentgrass biotypes on the competitive ratios for the relative number of grains (CRgn) and relative biomass of plants (CRb) in 2018–2019 (Table S9). The proportion of plants in the mixture was significant for CRgn. The site × bentgrass biotype interaction was significant for both CRgn and CRb. Additionally, CRgn was significantly determined by the WW proportion × bentgrass biotype interaction.

Figure 6. The substitutive competition model for the relative biomass yield of winter wheat (WW) and bentgrass in the 2018–2019 season, classified according to the *t*-test and *p*-values < 0.05. (a) Competition between WW and bentgrass with multiple herbicide resistance (RM), and (b) competition between WW and herbicide susceptible bentgrass (S). Legend: ○—WW; △—RS; ×—S; ■—RS + WW (a) or S + WW (b).

Figure 7. The substitutive competition model for the relative grain number of winter wheat (WW) and bentgrass in the 2018–2019 season, classified according to the *t*-test and *p*-values < 0.05. **(a)** Competition between WW and bentgrass with multiple herbicide resistance (RM), and **(b)** competition between WW and herbicide susceptible bentgrass (S). Legend: ○—WW; △—RS; ×—S; □—RS + WW (a) or S + WW (b).

In the 2018–2019 season, the CRgn was not correlated with the CRb ($r = 0.078$, $p = 0.479$). However, more dependencies between sites and biotypes were revealed (Figure 8). Firstly, compared to the previous season, the competitiveness of wheat, especially with regard to biomass, was lower for 64% of the combinations with RM and was in the range of 0.3–0.95. The WW displayed lower competitive effects toward the RM biotype in terms of both CRgn and CRb in Mydlniki, Wrocław, and Lipnik (50% of all RM combinations). On the contrary, WW was visibly more competitive toward the S biotype in Wrocław (CRb) and Mochełek (CRgn) and toward the RM biotype in Czesławice (Cz 0.4 RM and Cz 0.6 RM) and Winna Góra (WG 0.4 RM and WG 0.6 RM).

Figure 8. The distribution of sites × winter wheat proportion in the mixture × bentgrass biotypes for the competitive ratio indices calculated for the relative number of grains (CRgn) and relative biomass of plant (CRb) in 2018–2019. Legend: The sites of experiments: Lp—Lipnik, Mch—Mochełek, Cz—Czesławice, Sw—Swojczyce, Wr—Wrocław, WG—Winna Góra, Md—Mydlniki; 0.4 and 0.6—40% and 60% proportion of winter wheat in the mixture; RM—bentgrass biotype with a multiple resistance; S—susceptible biotype.

The CVA was also performed in 2018–2019 for WW. The first canonical variable was positively correlated with the WW biomass and negatively with the grain yield. The second canonical variable was positively determined by the WW length, the TGW, and the day-difference between the emergence of WW and B, and negatively with WW biomass and the number of grains (Table S10).

The two canonical variables accounted for 90.04% of the total multi-variability between the individual combinations (Figure 9). In 2018–2019, WW performed best in competition with both the RM and S biotypes in Wrocław, Mydlniki, and Mochełek and the RM biotype in Swojczyce. Interestingly, those sites differed significantly in weather conditions in 2018–2019, represented here as a hydrothermal coefficient K, i.e., the vegetative season in Wrocław and Mochełek was dry, Mydlniki was humid, and Swojczyce was relatively dry. On the contrary, the poorest competitive abilities of WW, in competition with both RM and S bentgrass, were noted in Lipnik, and also in Winna Góra (dry seasons in both sites), especially in competition with the RM biotype.

Figure 9. Distribution of seven sites where the competition of winter wheat (WW) was tested against bentgrass with multiple herbicide resistance (RM) or susceptible (S) in 2018–2019, based on five biological parameters of WW, in the space of the first two canonical variables (V1 and V2). Sites: Lp—Lipnik, Mch—Mochełek, WG—Winna Góra, Cz—Czesławice, Sw—Swojczyce, Wr—Wrocław, Md—Mydlniki. Subscript “r” denotes the competition of WW with RM and the subscript “s” with S.

4. Discussion

The three biotypes of bentgrass of different herbicide susceptibility, i.e., one with a single resistance to ALS inhibitor, one with a multiple resistance to ALS and ACC-ase inhibitors, and the susceptible one, displayed different competitive abilities toward winter wheat cv. Arkadia. The competition with a biotype with single resistance affected the number of winter wheat grains more. On the contrary, the biotype with multiple resistance to herbicides reduced the biomass of wheat. There are not many results regarding the competitiveness of wheat against herbicide-resistant and sensitive bentgrass biotypes, and those published did not indicate differences in competitive effects between herbicide-resistant and -susceptible biotypes toward wheat [18]. Similarly, no differences in the competitiveness of herbicide-resistant and herbicide-sensitive blackgrass (*Alopecurus myosuroides* Huds.) populations against wheat were demonstrated, using the target-neighborhood design model [37]. However, in another experiment, where the replacement series design was applied, competitive effects were found for wheat in association with an herbicide-susceptible *Raphanus raphanistrum* (L.), compared to the ALS-resistant one [38].

A holistic explanation of the problem of competition between winter wheat and herbicide-resistant/-susceptible bentgrass was found using canonical variate analysis for both seasons. In 2017–2018, wheat was more competitive toward the herbicide-susceptible bentgrass biotype in western Poland, i.e., Wrocław (southwest, relatively dry season) and Lipnik (northwest, humid season). In 2018–2019, wheat was characterized by increased competitiveness against both bentgrass biotypes, herbicide susceptible and with multiple herbicide resistance, in southern Poland in Wrocław and Mydlniki, and in northern Poland in Mochełek. In some sites this could be explained by the fact that wheat emerged fast and its seedlings were ahead of the bentgrass emergence. Many authors have emphasized that the early emergence of winter cereals, earlier also than the emergence of weeds, is

crucial in their increased competitiveness against weeds and the resulting yield of wheat grains [7,39–41].

Based on the competitive ratio indices, we found that weather course and soil conditions in the study sites influenced the competitiveness of winter wheat against both herbicide-resistant and -sensitive bentgrass biotypes. Wheat was less competitive with the bentgrass biotypes during the dry season, especially with regard to plant biomass, compared to the season classified as humid or optimal. In other studies, [8] found a reverse situation of increased competitiveness of wheat toward two dicotyledonous weeds, namely, *Papaver rhoeas* (L.) and *Viola arvensis* (Murray), during the summer drought, which restricted late weed growth. Wheat is a crop that is especially sensitive to drought, which causes several negative biochemical, physiological, and morphological changes [42]. However, the drought resistance of wheat is cultivar dependent. Under drought conditions, some wheat cultivars produce less vegetative biomass in order to maintain the highest possible seed production [43,44]. In our research, the drought stress in the 2018–2019 season resulted in increased competition of wheat cv. Arkadia with the sensitive biotype of bentgrass for seed production.

In summary, based on the replacement series design, it was shown that during the wet season, wheat cv. Arkadia was more competitive against both bentgrass (*A. spica-venti*) biotypes, i.e., with single resistance and the sensitive one. During dry season, the bentgrass with multiple resistance was more competitive toward wheat in terms of plant biomass but not in terms of grain production. The competitive effects of winter wheat toward the susceptible or herbicide-resistant biotypes of bentgrass were also site-specific and weather dependent.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/agronomy11050871/s1>, Table S1: Sum of precipitation and mean temperatures during the 2017–2018 season in the sites of study; Table S2: Sum of precipitation and mean temperatures during the 2018–2019 season in the sites of study; Table S3: The *t*-test values and *p*-values for comparison between empirical and theoretical models for biomass competition in replacement series design in 2017–2018; Table S4: The *t*-test values and *p*-values for comparison between empirical and theoretical models for grain number per plant competition in replacement series design in 2017–2018; Table S5: Mean squares from the three-way analysis of variance for the competitive ratio of winter wheat (WW) and herbicide-resistant or -susceptible bentgrass (B) calculated for the relative plant biomass (CRb) and relative grain number (CRgn) at two plant ratios 6WW:4B and 4WW:6B in the 2017–2018 season; Table S6: Results of discrimination analysis for the first and second canonical variable (cv1, cv2) for seven parameters of winter wheat (WW) in competition with herbicide-resistant or -susceptible bentgrass (B; *A. spica-venti*) in 2017–2018, depending on hydrothermal conditions and soil texture in the study sites; Table S7: The *t*-test values and *p*-values for comparison between empirical and theoretical models for biomass competition in replacement series design in 2018–2019; Table S8: The *t*-test values and *p*-values for comparison between empirical and theoretical models for grain number per plant competition in replacement series design in 2018–2019; Table S9: Mean squares from the three-way analysis of variance for the competitive ratio of winter wheat (WW) and herbicide-resistant or -susceptible bentgrass (B) calculated for the relative plant biomass (CRb) and relative grain number (CRgn) at two plant ratios 6WW:4B and 4WW:6B in the 2018–2019 season; Table S10: Results of discrimination analysis for the first and second canonical variable (cv1, cv2) for seven parameters of winter wheat (WW) in competition with herbicide-resistant or -susceptible bentgrass (B; *A. spica-venti*) in the 2019 season, depending on hydrothermal conditions and soil texture in the study sites.

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