

Article

Emergence and Phenological Development of Herbicide-Sensitive and Herbicide-Resistant Biotypes of *Apera Spica-Venti* and Winter Wheat under Competition

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Abstract: As a result of intensive herbicide protection of crops against silky bentgrass (*Apera spica-venti* (L.) P. Beauv.), numerous herbicide-resistant biotypes have been selected, mainly from the group of acetolactate synthase (ALS) inhibitors. We analyzed the development of herbicide-sensitive and herbicide-resistant biotypes of bentgrass and winter wheat under competition, taking into account selected physical and chemical properties of the soil, including nitrogen fertilization. The pot experiment (additive model) was conducted in the 2018/19 and 2019/20 seasons. The experimental factors included: (1) bentgrass with different sensitivity levels to herbicides from the groups HRAC/WSSA 1 and HRAC/WSSA 2, specifically two sensitive and three resistant biotypes; (2) two types of soil, sandy and clay; and (3) nitrogen fertilization, both with and without fertilization. Winter wheat and bentgrass development was assessed during each growing season, every 5 or 3 days from September until May, using the BBCH scale. The emergence date of the tested species/biotypes was recorded. The development of competing species was compared based on a new, proposed index: the duration of the developmental phases. As a result, the soil type and fertilization level differentiated wheat and bentgrass emergence dates and development. The autumn development of the competing species was slower and more uniform than the spring one. At the same time, the dynamics of the bentgrass and wheat development in the spring were greater. Bentgrass and winter wheat emerged earlier and grew more intensively on clay and fertilized soil. To sum up, no clear relationship was found between the resistance/sensitivity of bentgrass to herbicides and changes in the phenological development of plants in competition with winter wheat.

Keywords: additive model; silky bentgrass; BBCH scale; emergence; duration of the developmental phases



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1. Introduction

Silky bentgrass (*Apera spica-venti* (L.) P. Beauv.) is classified in the temperate climate of Europe as an annual winter weed, weeding mainly winter cereals and winter rapeseed [1–6]. As a result of intensive chemical protection of crops against bentgrass, numerous herbicide-resistant biotypes have been selected, mainly from the group of acetolactate synthase inhibitors [7–10]. Herbicide-resistant biotypes have been reported, among others, in the Czech Republic, Germany, Switzerland, Denmark, and Lithuania [11]. In Poland, the first biotypes of bentgrass resistant to chlorsulfuron, which belongs to the active substances from the group of ALS inhibitors, were recorded in 2000 [12].

Bentgrass is a weed that strongly competes with crops, even under conditions of so-called herbicide selection pressure [13,14]. In Poland, the economic threshold of bentgrass is assessed as 5–20 plants per 1 m² or 25–40 panicles per 1 m² [5,15].

The intensity of interspecific competition between crops and weeds in an agroecosystem is based on differences in the magnitude of ecological indicators, including crop yield [16,17]. Understanding these interactions, both at the inter- and intra-specific levels, is essential in developing a cost-effective and sustainable weed management strategy, especially in times of an increasing global problem with herbicide-resistant weeds [18]. Research on competitiveness can provide valuable information for farmers and producers of plant protection products [19,20]. Such research also constitutes an important aspect of the study of the ecology and physiology of plants in terms of the morphological and physiological costs that are associated with the acquisition of herbicide resistance and the invasive potential of resistant biotypes [21,22]. Studies on differences between herbicide-resistant and -susceptible weed biotypes provide valuable information for understanding the ecology of resistant weeds. Such studies should include analysis of differences in seed germination and morphology, physiology, and/or phenology between S and R biotypes throughout the weed life cycle [23,24]. The results of the observations can be used to develop practices and strategies for combating resistant weed biotypes. The competitiveness of weeds may vary significantly depending on the biotype [25], and weeds are one of the main limitations to yield in agricultural production [26].

Often, in the absence of herbicide use, resistant weed biotypes are characterized by the so-called fitness cost [25,27–29]. The fitness of resistant biotypes is related to the biological and morphological changes in the plant. It depends on the place of origin of the weed biotype (including field history) and the local characteristics of the weed population [20]. Therefore, there is a need to study the fitness phenomenon occurring in herbicide-resistant bentgrass biotypes originating from geographically diverse locations in the context of their competitiveness with crops.

This work aimed to analyze the development phases of herbicide-sensitive and herbicide-resistant biotypes of bentgrass and winter wheat under competitive conditions, depending on selected physical and chemical properties of the soil substrate and the level of nitrogen fertilization in pot experiments carried out during two vegetative seasons.

2. Material and Methods

2.1. Confirmation of Resistance

The biological material consisted of grains of three herbicide-resistant bentgrass biotypes and two sensitive ones. The resistance or sensitivity of biotypes to herbicides from various HRAC/WSSA groups was confirmed by biological tests carried out in the glasshouse of the University of Agriculture in Krakow in the year 2018, according to the method described by [30]. In brief, pots (5.5 cm diameter) with *A. spica-venti* (3 plants per pot) were set up in a complete randomized design with 3 replicates. At the proper growth stage, i.e., emergence or 2–3 leaves, plants were sprayed with different doses of herbicides: N0, N1/2, N1, N2, N4, N8, N16, or N32, where N refers to the field dose. A susceptible population was taken for comparison. The herbicides were applied using a precision bench sprayer (APORO Sp. z o.o., Poznań, Poland), with a boom equipped with one flat-fan hydraulic Teejet XR 11002 VP nozzle and calibrated to deliver 200 L ha^{−1} of spray at a pressure of 200 bars. Three weeks after herbicide application, the aboveground plant biomass was cut and weighed (fresh biomass). The ED50 dose, i.e., the dose causing a 50% reduction in the biomass of a herbicide-treated plant, was designated, and the RI index [31] was calculated. The RI was as follows: S—susceptibility (<2); r—reduced susceptibility (2–2.9); R—low resistance (3–5); RR—moderate resistance (6–10); RRR—high resistance (11–71.4). The characteristics of individual biotypes are presented in Table 1.

Table 1. Characteristics of silky bentgrass biotypes (*Apera spica-venti* (L.) P. Beauv.) used in the experiments.

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/	1	RR	2013	Nowa Cerkiew (Poland) 53°51'58" N; 18°39'27" E
		chlorsulfuron/	2	RR		
		iodosulfuron methyl sodium/	2	RRR		
		mesosulfuron methyl	2	RR		
S1	--	sensitive	-	S	2012	Sitno (Poland) 53°11'10" N; 16°01'46" E
S2	--	sensitive	-	S	2016	Poland

Legend: RI—resistance index (S—susceptible; R—low resistance; RR—moderate resistance; RRR—high resistance). Table 1 was prepared based on data from the project “Anti-resistance strategy in weed management as an important factor of the sustainable development of agroecosystem” [funded by the National Center for Research and Development; contract number: 3/347445/1/NCBR/2017].

2.2. Pot Experiment

The winter wheat was cv. Arkadia (registration year 2011) from the elite and quality group (E/A), breeder: Danko Hodowla Plant Sp. z o. o. (Choryn, Poland). It is a cultivar with good winter hardiness and tillering ability. It tolerates soil acidification well, making it suitable for cultivation throughout Poland. It is characterized by a medium-long blade (102 cm) and early earing and ripening. The grain is uniform, with an average MTS of 46 g.

Until the experiment, bentgrass seeds were stored at 4 °C. The pot experiment was carried out in two growing seasons, 2018/2019 and 2019/2020, in a vegetation hall secured with a garden net, with access to rainwater and natural air circulation. The experiment was set up in a completely randomized design, with three repetitions.

The research factors in the experiment included (1) biotypes of bentgrass with different levels of sensitivity to herbicides from the group of ACCase inhibitors (HRAC/WSSA 1) and ALS inhibitors (HRAC/WSSA 2), including two sensitive biotypes (S1, S2) and three resistant biotypes (B1, B2, AB); (2) type of soil substrate: 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) (Table 2); and (3) level of nitrogen fertilization: without fertilization (a0) and with fertilization at the dose recommended for winter wheat cv. Arkadia (a1) equivalent to 300 kg ha^{−1}.

Table 2. Physicochemical characteristics of soils used in the pot experiment.

Soil Texture % *					
Soil	<2 µM	2–20 µM	20–50 µM	50–2000 µM	Soil Classification
C	5.8	28.3	29.6	36.4	Clay loam
S	1.7	10.2	9.2	78.9	Sandy loam
Chemical Soil Characteristics **					
Soil	pH _{KCl}	P ₂ O ₅ [mg/100 g]	K ₂ O [mg/100 g]	Mg [mg/100 g]	N Total [%]
C	6.7	9.1	15.8	5.9	0.1
S	5.4	13.8	9.5	2.5	0.1

* Analysis using a laser particle meter. ** pH in KCl [32] PN-ISO 10390:1997. Phosphorus—colorimetric method [33] PN-R-04023:1996, potassium—flame photometry method [34] PN-R-04022:1996+Az1), magnesium—FAAS method [35] PN-R-04020:1994+Az1:2004, excl. point 3, total nitrogen—titration method (PB17 ed.4).

Plastic pots with a capacity of 18 L (upper diameter 31 cm, height 27 cm) were filled with fresh topsoil of one of two soil substrates (C or S) and sifted through a sieve with a mesh diameter of 0.5 cm. In the fertilized pots, the nitrogen fertilizer (NPK(MgS) 5-16-24-(4-7)) was applied before sowing at a dose of 2.26 g per pot. The fertilizer was mixed with the soil,

and plants were sown into the prepared substrate. The plants were sown in pots according to the additive competitiveness model [36] at the optimal date for sowing winter wheat: 29 September 2018 and 28 September 2019. Wheat and bentgrass were sown on the same day. Winter wheat grains were sown in pots according to the optimal density specified by the breeder (375 pieces per m²) at a 2–3 cm depth. Bentgrass seeds were sown between wheat rows to a depth of approximately 0.5 cm. The number of plants per pot was 30 in the case of winter wheat and 5 in the case of wheat bentgrass. A higher number of bentgrass seeds (by 30%) was used to secure the planned weed density; after emergence, plants were thinned to five per pot. Each pot contained winter wheat plants and one biotype of bentgrass. The control treatment consisted of only winter wheat. The second dose of nitrogen fertilization (ammonium nitrate 34N) was applied in spring during the shooting phase of winter wheat stalks (BBCH 31–33) in an amount of 0.95 g per pot.

The proper growth and development of the plants were ensured by manually removing undesirable weeds. Every year, during the earing phase (BBCH 51–59) and flowering of winter wheat (BBCH 61–69), deltamethrin (Decis Mega 50 EW, Bayer) was applied against aphids. No fungal diseases or other pests were recorded. Manual soil irrigation was provided in drought at 5–7 day intervals until precipitation occurred.

The developmental stages of winter wheat and bentgrass plants were recorded during each growing season, expressed on the BBCH scale [37]. Observations began with the emergence of one of the tested species/biotypes. The beginning of emergence was defined as the day when the first leaf of the first plant representing a given species/biotype emerged from the leaf sheath (BBCH 10). Measurements of BBCH phases were carried out in autumn and spring vegetation. The autumn period included the days between the sowing date and the end of November, which was assumed to be the beginning of the winter dormancy period of plants; the spring vegetation period included the days between the noticeable growth and development of plants in March/April until the harvest of the tested plants before the weed seeds were shed. In the initial period of plant vegetation, i.e., in autumn and early spring, measurements were taken every 5 days. From the moment of intensified vegetation, when plant biomass grew visibly faster, measurements were made every 3 days. The development phase was considered complete for a cultivated plant when 50% of the individuals were in a given BBCH phase. In turn, the weed's phases were determined individually for each specimen.

Table 3 presents the air temperature during the study period compared to the multi-year period (1971–2010). The average temperatures in the 2018/2019 and 2019/2020 seasons were similar and by ca. 2 °C higher than for the multi-year period. The season 2018/19 was specifically warm in April–May. On the contrary, the 2019/20 season was specifically warmer in March–April and June–August compared to the multi-year period.

Table 3. Air temperature [°C] in the 2018/2019 and 2019/2020 seasons.

Season	Month												Mean Temperature
	IX	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	
2018/2019	13.3	8.2	3.3	−0.9	−0.9	−2.7	1.4	15.7	16.9	18.8	20.1	21.3	9.5
2019/2020	13.2	8.7	3.7	−0.8	−2.1	−0.5	9.3	10.8	12.0	21.0	19.6	20.3	9.7
1971–2010	13.3	8.4	3.1	−0.8	−2.3	−0.8	3.1	8.3	13.7	16.5	18.3	17.8	7.7

2.3. Statistical Analyses

Based on the number of days covering each of the observed BBCH developmental phases, the new parameter called the weighted average duration of the developmental phase (WDT) of winter wheat plants and silky bentgrass plants was proposed and calculated according to the following formula:

$$\text{WDT} = \frac{\sum_{i=1}^p (t_i \cdot w_i)}{\sum_{i=1}^p w_i}$$

where p is the number of observed BBCH phases, t is the number of days covering a given phase, and w is the BBCH phase code.

The WDT index reports the average duration of phases and shows which phases may have had a longer or shorter duration. The WDT increases or decreases rapidly when high-code BBCH phases are lengthened or shortened, while changes in the duration of low-code phases have a lower impact on changing the WDT value.

The WDT for a given pot was calculated as the average WDT for winter wheat plants and silky bentgrass plants. The calculated values were subjected to a three-way ANOVA, where the factors were the biotype of bentgrass (representing the competition between the biotype and wheat), fertilization, and soil type. Mean values were compared using Duncan's multiple-range test.

3. Results

3.1. Date of Emergence of Winter Wheat and Silky Bentgrass

In October 2018, the average air temperature was similar to the multi-year period (Table 3). Weed-free winter wheat emerged 10 days after sowing, regardless of the soil substrate (S or C) and fertilization level (a0 or a1) (Table 4). Wheat emerged 10–13 days after sowing in the pots with bentgrass. The longer emergence time was for wheat competing with both sensitive bentgrass and resistant biotypes: B1 (soil S, a1) and AB (soil C, a0). Bentgrass emerged 14–18 days after sowing, with later emergence times recorded for the resistant biotype B1 (S and C soils, a0) and the sensitive biotypes S1 and S2 (soil S, a1).

Table 4. Sowing and emergence dates for winter wheat and silky bentgrass in autumn 2018.

Fertilization	Species	Sowing Date	Emergence Date	
			S soil	C Soil
NO	WW control	29 September 2018	9 October 2018	9 October 2018
	WW (+S1)		12 October 2018	9 October 2018
	WW (+S2)		12 October 2018	9 October 2018
	WW (+B1)		9 October 2018	9 October 2018
	WW(+B2)		9 October 2018	9 October 2018
	WW (+AB)		9 October 2018	12 October 2018
	S1		12 October 2018	12 October 2018
	S2		12 October 2018	12 October 2018
	B1		16 October 2018	16 October 2018
	B2		12 October 2018	12 October 2018
	AB		12 October 2018	12 October 2018
YES	WW control	29 September 2018	9 October 2018	9 October 2018
	WW (+S1)		9 October 2018	12 October 2018
	WW (+S2)		9 October 2018	9 October 2018
	WW (+B1)		12 October 2018	9 October 2018
	WW(+B2)		9 October 2018	9 October 2018
	WW (+AB)		9 October 2018	9 October 2018
	S1		16 October 2018	12 October 2018
	S2		16 October 2018	12 October 2018
	B1		12 October 2018	12 October 2018
	B2		12 October 2018	12 October 2018
	AB		12 October 2018	12 October 2018

Legend: WW (+S1–AB)—the emergence of winter wheat competing with resistant or susceptible silky bentgrass, S—the emergence of sensitive bentgrass, B—the emergence of single resistant bentgrass, AB—the emergence of multiple resistant bentgrass.

In October 2019, the average air temperature was 0.5 C higher than the previous year (Table 3). Wheat emerged similarly to the previous season, i.e., 10–13 days after sowing (Table 5). At the same time, contrary to the previous season, the earlier date of wheat emergence concerned pots in which wheat competed with biotypes S1, S2, B1, and AB. Wheat emerged faster in S and a0 soil and C and a1 soil. Bentgrass emergence was recorded 13–19 days after sowing. Both sensitive biotypes and resistant biotype B1 emerged slower in pots with S, a1 soil.

Table 5. Sowing and emergence dates for winter wheat and silky bentgrass in autumn 2019.

Fertilization	Species	Sowing Date	Emergence Date	
			S Soil	C Soil
NO	WW control	28 September 2019	12 October 2019	9 October 2019
	WW (+S1)		9 October 2019	12 October 2019
	WW (+S2)		9 October 2019	12 October 2019
	WW (+B1)		9 October 2019	9 October 2019
	WW(+B2)		12 October 2019	12 October 2019
	WW (+AB)		9 October 2019	9 October 2019
	S1		16 October 2019	16 October 2019
	S2		18 October 2019	18 October 2019
	B1		18 October 2019	16 October 2019
	B2		12 October 2019	12 October 2019
	AB		12 October 2019	16 October 2019
YES	WW control	28 September 2019	9 October 2019	12 October 2019
	WW (+S1)		9 October 2019	9 October 2019
	WW (+S2)		12 October 2019	12 October 2019
	WW (+B1)		9 October 2019	9 October 2019
	WW(+B2)		12 October 2019	9 October 2019
	WW (+AB)		9 October 2019	9 October 2019
	S1		16 October 2019	16 October 2019
	S2		12 October 2019	16 October 2019
	B1		12 October 2019	12 October 2019
	B2		12 October 2019	12 October 2019
	AB		12 October 2019	12 October 2019

Legend: WW (+S1–AB)—the emergence of winter wheat competing with resistant or susceptible silky bentgrass, S—the emergence of sensitive bentgrass, B—the emergence of single resistant bentgrass, AB—the emergence of multiple resistant bentgrass.

3.2. The Development of Winter Wheat and Silky Bentgrass in the 2018/2019 Season

In the experiment carried out in the 2018–2019 season, in the autumn period, the examined factors had no significant impact on the average duration of individual development phases (WDT) (Table 6). Very similar durations of BBCH phases 10, 11, 12, 13, 21, and 22 were observed, both in control pots (winter wheat only) and pots in which wheat and the bentgrass biotype competed with each other, regardless of fertilization level and soil type (Supplementary Figures S1–S4). The calculated WDT ranged from 3 days in the case of wheat competition with the B2 biotype to 3.5 days in the wheat competition with the B1 biotype and mainly depended on the duration of the BBCH phases 10–13.

At the end of autumn vegetation 2018, bentgrass was at the beginning of the tillering phase (approximately 60% of plants) in the pots with light soil (S) (Supplementary Figures S1 and S2). Bentgrass biotypes growing on C, a0 soil entered the winter dormancy in the two- or three-leaf phase (Supplementary Figure S3). Regarding the sensitive S1 biotype on C, a1 soil (Supplementary Figure S4), approximately 20% of the plants finished the autumn vegetation in the tillering phase (BBCH 21).

Table 6. Three-way ANOVA for a weighted average duration of the developmental phase in pots containing silky bentgrass biotypes competing with winter wheat in 2018/2019.

Source of Variation	Degrees of Freedom	Autumn 2018		Spring 2019	
		F Value	p-Value	F Value	p-Value
Biotype	5	1.231	0.309	2.848	0.025
Fertilization	1	0.281	0.598	63.559	<0.01
Soil type	1	0.646	0.426	2.935	0.093
Biotype × Fertilization	5	2.342	0.056	3.160	0.015
Biotype × Soil type	5	1.557	0.190	0.593	0.704
Fertilization × Soil type	1	1.052	0.310	1.571	0.216
Biotype × Fertilization × Soil type	5	0.509	0.768	3.154	0.015
Residuals	48	-	-	-	-

Note: bold *p*-values designate significant source of variation according to F test at *p* < 0.05.

In the spring of 2019, the development phases indicated a significant impact of the biotype's competition with wheat, fertilization, and the interaction between these factors on the WDT (Table 6). A significant interaction was also found between all analyzed factors. The average development phase duration was much shorter than the autumn assessment, and WDT was approximately 1.5 days. Mainly, variability was observed during BBCH phases 21–24 and 30–37 (Supplementary Figures S5–S8).

In spring 2019, winter wheat began vegetation in the tillering phase (BBCH 21–23) (Supplementary Figures S5 and S7), whereas bentgrass was, in most cases, in the BBCH 14–15 phase (Supplementary Figures S5–S8). At the end of May, the plants reached the flag leaf stage in all treatments. On clay-fertilized soil (C, a1), approximately 80% of bentgrass plants reached the BBCH 43 stage, regardless of the biotype (Supplementary Figure S8).

Control wheat developed the slowest in pots with S soil, but after fertilization, the average duration of development phases was significantly shortened (Table 7). Competition between the bentgrass biotype and wheat shortened the average duration of wheat development phases. A relatively long WDT of wheat ranging from 1.32 to 1.45 days was observed for pots with herbicide-sensitive bentgrass biotypes S1 and S2. The lower of these values occurred in the case of pots with C soil and fertilization. Regardless of the fertilization and soil type, wheat plants in pots with the resistant biotype B2 developed the fastest; the average WDT for these plants ranged from 1.23 to 1.28 days. In the case of wheat competition with the B1 biotype, the use of C soil and fertilization resulted in a significant slowdown in development (average WDT > 1.6 days). However, in pots where the resistant AB biotype competed with wheat without fertilization, both soil types showed an increase in the average WDT, especially compared to the B2 biotype.

Table 7. Differentiation of the weighted average duration of developmental phases (WDT) depended on the silky bentgrass competing with winter wheat, soil type, and fertilization in the 2018/2019 season.

Biotype	Soil Type	Fertilization	
		a0	a1
WW (control)	S	1.64 a #	1.46 cdef
	C	1.48 bcd	1.30 fghij
WW + S1	S	1.45 cdefg	1.39 cdefghi
	C	1.41 cdefghi	1.34 defghij
WW + S2	S	1.42 cdefgh	1.40 cdefghi
	C	1.40 cdefghi	1.32 efghij
WW + B1	S	1.44 cdefg	1.30 ghij
	C	1.31 efghij	1.64 a

Table 7. Cont.

Biotype	Soil Type	Fertilization	
		a0	a1
WW + B2	S	1.28 hij	1.28 hij
	C	1.26 ij	1.23 j
WW + AB	S	1.60 ab	1.28 hij
	C	1.46 cde	1.26 ij

#—mean values followed by the same letter(s) are not significantly different according to the Duncan multiple range test ($p < 0.05$).

3.3. The Development of Winter Wheat and Silky Bentgrass in the 2019/2020 Season

In the experiment conducted in 2019/2020, in the fall of 2019, a significant impact of the biotype competing with wheat and the fertilization level on the average WDT was found (Table 8). On average, in the autumn period, the WDT was about 2.8 days, and the greatest impact on extending this time was from the BBCH phases 10–13 (Supplementary Figures S9–S12).

Table 8. Three-way ANOVA for a weighted average duration of the developmental phase in pots containing silky bentgrass biotypes competing with winter wheat in season 2019/2020.

Source of Variation	Degrees of Freedom	Autumn 2019		Spring 2020	
		F Value	p-Value	F Value	p-Value
Biotype	5	3.280	0.012	6.980	<0.01
Fertilization	1	42.886	<0.01	21.505	<0.01
Soil type	1	0.918	0.342	0.072	0.789
Biotype × Fertilization	5	1.158	0.343	2.584	0.038
Biotype × Soil type	5	0.433	0.823	1.966	0.101
Fertilization × Soil type	1	0.619	0.435	0.025	0.876
Biotype × Fertilization × Soil type	5	1.360	0.256	1.227	0.311
Residuals	48	-	-	-	-

Note: bold p -values designate significant source of variation according to F test at $p < 0.05$.

Wheat reached the developmental phases at similar dates (Supplementary Figures S9–S12). No wheat plants in the tillering phase were recorded in pots with B1 and AB biotypes on light and unfertilized soil (S, a0) (Supplementary Figure S9).

Winter wheat in control pots was characterized by a similar average WDT, approximately 3 days, as in the case of pots with the susceptible biotypes S1 and S2 and the resistant biotype AB (Table 9). The shortest WDT, approximately 2.5 days, was observed in the case of the resistant biotype B1. Regardless of the tested biotype, fertilization shortened the average WDT by approximately 0.5 days.

The results obtained in the spring series of measurements in 2020 indicate a significant impact of the bentgrass biotype competing with winter wheat, fertilization, and the interaction between these factors on the average WDT (Table 10). The WDT value was determined primarily by BBCH phases 21–37 (Supplementary Figures S12–S16). The shortest WDT, approximately 1.6 days, was found in control pots without bentgrass biotypes competing with wheat (Table 10). However, wheat plants and competing herbicide-sensitive biotypes were characterized by a shorter average WDT compared to pots with resistant biotypes B1 and B2. In control pots, using fertilization resulted in a significant reduction in the WDT by approximately 7%. A similar relationship was found for pots in which winter wheat competed with the sensitive biotype S2 and the resistant biotype B2, with the WDT shortening by 10%.

Table 9. Differentiation of weighted average duration of developmental phases depending on the silky bentgrass competing with winter wheat and fertilization in autumn 2019.

Biotype	Weighted Average Duration of Phase
WW (control)	2.81 ab [#]
WW + S1	2.88 ab
WW + S2	2.96 a
WW + B1	2.45 c
WW + B2	2.58 bc
WW + AB	2.81 ab
Fertilization	
a0	3.04 a
a1	2.46 b

[#]—mean values followed by the same letter(s) are not significantly different according to the Duncan multiple range test ($p < 0.05$).

Table 10. Differentiation of weighted average duration of developmental phases (WDT) depending on the silky bentgrass competing with winter wheat and fertilization in spring 2020.

Biotype	Fertilization	
	a0	a1
WW (control)	1.66 cde [#]	1.55 f
WW + S1	1.72 bcd	1.66 cde
WW + S2	1.73 bcd	1.59 ef
WW + B1	1.77 abc	1.80 ab
WW + B2	1.84 a	1.65 def
WW + AB	1.72 bcd	1.65 def

[#]—mean values followed by the same letter(s) are not significantly different according to the Duncan multiple range test ($p < 0.05$).

Winter wheat growing on sandy soil differed in development up to BBCH 43 (Supplementary Figures S13 and S14) and on clay soil up to BBCH 51 (Supplementary Figures S15 and S16). Bentgrass started spring vegetation in 2020 in the early tillering phase (BBCH 21–23). Regardless of the biotype, plants growing on unfertilized sandy or clay soil reached BBCH 43 at the beginning of June (Supplementary Figures S13 and S15). All bentgrass biotypes growing on sandy, fertilized soil reached the flag leaf development (BBCH 37) at the end of May (Supplementary Figure S14).

4. Discussion

Weeds compete strongly with crops and easily adapt to diverse environmental conditions [38–40]. In turn, crop plants whose individual agricultural varieties are adapted to optimal habitat conditions are often less competitive against weeds, including herbicide-resistant biotypes [41–43]. Therefore, it is crucial to know how weeds with different levels of resistance to herbicides will compete with crops and whether resistant biotypes will incur a cost from acquiring so-called resistance. For instance, the fitness cost incurred by resistant biotypes, when compared to herbicide-sensitive biotypes, could significantly influence their competitive ability [44,45].

In our research, during two seasons, the influence of soil and fertilization on the emergence date and competitiveness of winter wheat and silky bentgrass with different levels of sensitivity/resistance to herbicides was assessed. Our research proved that the factors determining the date of wheat and weed emergence were the type of soil substrate, the level of fertilization, and temperature. For example, in autumn 2018, wheat in competition

with sensitive biotypes in light unfertilized and fertilized soil emerged 3 days later than both sensitive and resistant biotypes B2 and AB. In the fall of 2019, wheat emerged 3 days earlier in competition with the same biotypes in the same soil conditions. The available scientific literature does not contain many examples of analyzing the soil type as a factor modifying the competition of a crop with resistant and sensitive weed biotypes. Similar research was conducted by [45], who examined *Alopecurus myosuroides* biotypes resistant to the use of herbicides from the group of ACCase inhibitors (fenoxaprop-P-ethyl), microtubule formation inhibitors (pendimethalin), lipid synthesis inhibitors (prosulfocarb), and ALS inhibitors (flupyr-sulfuron-methyl). They used three types of soil substrate for research. The authors showed that the emergence of the R biotype was slower and occurred in fewer numbers than that of the S biotype, regardless of the soil substrate tested. However, [46,47] claimed that the herbicide resistance trait reduces the weed's ability to compete for nutrients, especially nitrogen.

Based on analyses of the new proposed index called the weighted average duration of the developmental phase (WDT), we found certain trends in the development of the tested plants in competition. In autumn, the WDT index values were higher, pointing to a slower development of plants. However, the development phases were even, especially in the 2018 season. In that season, regardless of the research variant used, wheat reached subsequent development stages faster, and the BBCH stages it achieved at the end of autumn vegetation were higher than those in the tested bentgrass biotypes. On the contrary, in the fall of 2019, a significant impact of the bentgrass biotype competing with wheat, combined with the fertilization effect, on the average WDT was found. Wheat developed faster in competition with the B1 biotype.

Moreover, fertilization sped up the development of competing plants. The competitive impacts of weeds on crop growth, development, and yield typically occur during the first 30–40 days after sowing [48,49]. This is also confirmed by the results of [50] for *Conyza canadensis* and [51] for *Lolium multiflorum*. Other research by [48] reports that *A. spica-venti* is less competitive in the early stages of growth, mostly due to seedlings' morphological characteristics. Still, its development rate increases significantly in spring, with an intensive biomass increase, and it can even outgrow the wheat crop before the earing stage, thus competing more strongly with it in later stages of development. Research by [52], in turn, indicates that the competitiveness of *A. myosuroides* against winter wheat depends largely on climatic conditions and the type of soil on which the test plants grow. Similar observations were made by [53], analyzing the competitiveness between winter wheat and *Centaurea cyanus*.

Our research showed that competition between the bentgrass biotype and winter wheat shortened the average duration of wheat development phases during spring vegetation, which was especially influenced by the BBCH phases 21–37 (tillering and stem elongation). The soil substrate type and fertilization level also influenced the variable development of winter wheat and bentgrass. In clay, fertilized soil plants, on average, developed faster. However, the competitiveness was not dependent on the herbicide-resistance level. According to general ecological theories, herbicide-resistant weed biotypes are predicted to incur a cost for acquiring resistance (fitness cost) without herbicide application [54]. However, acquiring an herbicide-resistant gene is not always associated with incurring fitness costs [55]. Numerous reports, including our research, indicate that the appearance of a stress factor (variable soil and fertilization conditions in our research) will not always be associated with incurring fitness costs in R biotypes. This may enhance the durability of resistant individuals within the biocenosis and increase their competitiveness towards cultivated plants, as also indicated by [56,57].

In summary, we did not prove a clear difference between the effects of herbicide-sensitive and herbicide-resistant biotypes of bentgrass on the development of winter wheat under competition. However, based on a new proposed index, the weighted average duration of the developmental phase (WDT), we found the development of competing bentgrass and winter wheat cv. Arkadia was slower in the fall and more dynamic in the

spring. In that period, the WDT index was mostly influenced by BBCH phases 21–37. Winter wheat development was slower without competing silky bentgrass, especially on sandy soil without nitrogen fertilization. The temperature course could have influenced the development of plants during their growth, but this effect needs more detailed studies.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture14060945/s1>, Figure S1: Developmental phases (BBCH) of winter wheat and silky bentgrass during the autumn of 2018 on sandy loam (S), unfertilized (a0); Figure S2: Developmental phases (BBCH) of winter wheat and silky bentgrass during the autumn of 2018 on sandy loam (S), fertilized (a1); Figure S3: Developmental phases (BBCH) of winter wheat and silky bentgrass during the autumn of 2018 on clay loam (C), unfertilized (a0); Figure S4: Developmental phases (BBCH) of winter wheat and silky bentgrass during the autumn of 2018 on clay loam (C), fertilized (a1); Figure S5: Developmental phases (BBCH) of winter wheat and silky bentgrass during the spring and summer of 2019 on sandy loam (S), unfertilized (a0); Figure S6: Developmental phases (BBCH) of winter wheat and silky bentgrass during the spring and summer of 2019 on sandy loam (S), fertilized (a1); Figure S7: Developmental phases (BBCH) of winter wheat and silky bentgrass during the spring and summer of 2019 on clay loam (C), unfertilized (a0); Figure S8: Developmental phases (BBCH) of winter wheat and silky bentgrass during the spring and summer of 2019 on clay loam (C), fertilized (a1); Figure S9: Developmental phases (BBCH) of winter wheat and silky bentgrass during the autumn of 2019 on sandy loam (S), unfertilized (a0); Figure S10: Developmental phases (BBCH) of winter wheat and silky bentgrass during the autumn of 2019 on sandy loam (S), fertilized (a1); Figure S11: Developmental phases (BBCH) of winter wheat and silky bentgrass during the autumn of 2019 on clay loam (C), unfertilized (a0); Figure S12: Developmental phases (BBCH) of winter wheat and silky bentgrass during the autumn of 2019 on clay loam (C), fertilized (a1); Figure S13: Developmental phases (BBCH) of winter wheat and silky bentgrass during the spring and summer of 2020 on sandy loam (S), unfertilized (a0); Figure S14: Developmental phases (BBCH) of winter wheat and silky bentgrass during the spring and summer of 2020 on sandy loam (S), fertilized (a1); Figure S15: Developmental phases (BBCH) of winter wheat and silky bentgrass during the spring and summer of 2020 on clay loam (C), unfertilized (a0); Figure S16: Developmental phases (BBCH) of winter wheat and silky bentgrass during the spring and summer of 2020 on clay loam (C), fertilized (a1).

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