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Article

The Critical Period of Weed Control Influences Sunflower (*Helianthus annuus* L.) Yield, Yield Components but Not Oil Content

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Abstract: Field studies were conducted in the northeastern part of the Republic of Croatia to determine the influence of the critical period of weed interference on sunflower (*Helianthus annuus*) yield, yield components, and oil content. For this purpose, different durations of competition were established, allowing weeds to infest the crop for increasing periods of time after planting or maintaining plots weed-free for increasing periods of time after planting. The beginning and the end of the critical period of weed control (CPWC), based on a 5% and 10% loss of sunflower yield, were determined by fitting the four-parameter log-logistic equations to the relative seed yield. The total weed biomass increased progressively in relation to the increase in the competition. The beginning of the CPWC period, based on a 5% acceptable yield loss, ranged from 141 to 234 growing degree days (GDD), which corresponded to the two-to-four true leaf development stage (the V2–V4 growth stages) across both sites and years. The crop had to be kept weed-free until a period when sunflower inflorescence began to open and flower (the R4–R5 growth stage) or from 1365 to 1932 GDD. The sunflower yield and yield components varied between the years and among locations. An increasing duration of weed interference negatively affected crop height, head diameter, and 1000-kernel weight, but not seed oil content.

Keywords: sunflower (*Helianthus annuus* L.); timing of weed removal; weed interference; weed biomass accumulation; crop yield loss

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1. Introduction

Sunflower (*Helianthus annuus* L.) is one of the most important oil crops. It is grown on 29 million hectares over a wide geographical area. This crop meets more than 14% of the world's oil production demands, with an annual production of 58 million tons. It is grown primarily for use as an edible oil [1].

However, weed management in sunflower growth areas can be challenging since weeds, especially broadleaved weeds, can cause a substantial yield loss [2,3]. If this crop is subjected to full weed competition, weed infestation can reduce the yield of sunflower by 58% [4] or more [5]. Sunflower is not always a good competitor because of its slow growth in the initial stage [6]. Sunflower is planted in spacings of 70 cm rows, and usually with lower planting densities than those of many other row crops. This makes the crop more sensitive to weed competition, particularly during the first few weeks of its growth [7].

Weed interference with a crop depends on various factors, including weed associations, weed density, weed emergence time, the crop's life cycle, the time of crop planting, the soil, and the climatic conditions [8]. A combination of these factors can determine the length of tolerated competition and the weed-free period [9,10], and allow the establishment of the appropriate timing for weed control to prevent the crop's yield loss above a defined level [11].

The critical period of weed control is the period during which weed control is required to prevent yield losses [12]. This critical period comes in the middle of two other periods: the beginning of the vegetation season, when weeds do not need to be controlled; and the end of the growing season, when weeds cause insufficient yield loss to justify their control.

The critical period of weed removal has been determined for a variety of crops grown under various environmental conditions [13–15]. The results of some studies showed that site-specific factors, such as weed density, the time of weeds' emergence, and weed species' composition can affect the duration of the critical period [16,17]. In some studies, differences in the timing of the critical period were observed with different light intensities [18], crop densities, planting patterns [19], soil temperatures, moisture, and soil fertility [20].

Knowledge of the critical period is a helpful tool in planning reliable strategies when integrated weed management is based on the use of mechanical weed removal or well-timed post-emergence herbicides. Therefore, the objective of this research was to generate information about the critical period of weed control in sunflower based on the naturally occurring weed population in the agroecological conditions of northeastern Croatia.

2. Materials and Methods

2.1. Site Description

Field experiments were conducted in 2010 and 2011 on luvisol soil type (24% clay with a pH of 5.4 and an organic matter content of 2.1) near Valpovo (45°40′ N, 18°25′ E) and in 2014 and 2015 on eutric cambisol soil (24.1% clay with a pH of 6.4 and an organic matter content of 1.7) near Darda (45°38′ N, 18°42′ E) in Osijek-Baranja County. This region, which is situated in the northeastern part of the Republic of Croatia, has a moderate continental climate, with long and mild springs and autumns, and warm summers, which favors agricultural production.

The mean daily air temperatures during the study period did not deviate significantly from the long-term average, while the monthly rainfall varied in total amount and periodicity among the years (Table 1). In particular, May was a very humid month, with significantly greater amounts of rain during the study periods, except during the second year, when the monthly rainfall during the whole sunflower vegetation season was less than the 30-year average (Table 1).

Table 1. Average monthly air temperatures and monthly precipitation for the growing season from April to September in Valpovo (2010 and 2011) and Darda (2014 and 2015).

	Temperature (°C)					Precipitation (mm)				
	2010	2011	2014	2015	30-Year Average	2010	2011	2014	2015	30-Year Average
April	11.8	12.9	13.1	13.2	11.4	68.7	10.9	45.2	81.2	53.2
May	16.1	16.3	16.7	16.1	16.7	164.0	29.6	118.8	159.1	59.1
June	20.0	20.9	19.9	20.3	19.6	210.3	28.1	63.4	91.6	88.0
July	22.7	21.9	22.9	21.8	21.1	44.1	57.9	36.3	65.4	64.9
August	20.8	22.3	22.7	20.8	20.7	69.1	14.6	32.8	53.8	60.9
September	15.0	19.4	15.9	17.0	16.5	116.1	18.2	129.0	69.6	46.3

2.2. Experimental Design

A common cropping practice for sunflower growing in this region was applied in each study year [21]. Primary tillage consisted of deep ploughing in autumn followed by shallow ploughing in spring, harrowing, and seedbed preparation. Fertilizers were applied using the following recommended rates: 51 kg ha^{-1} N, 80 kg ha^{-1} P, and 120 kg ha^{-1} K in autumn, and 60 kg ha^{-1} N, 30 kg ha^{-1} P, and 30 kg ha^{-1} K at planting. The sunflower hybrid PR63A90 was seeded on 6 May 2010, 2 May 2011, 7 May 2014, and 4 May 2015, following a row spacing of 70 cm, with a planter set to deliver 70.000 seeds ha^{-1}. No pre-emergence or pre-plant herbicides were used during the study.

The experiment was laid out as a randomized complete block design with four replications. Two types of weed removal treatments were implemented from the start of crop emergence. The timing of weed removal was chosen according to the sunflower development stage [22]. The determination of the sunflower development stage was carried out by considering the number of fully developed leaves per plant (vegetative growth) or various flowering stages (reproductive growth) by examining 10 consecutive plants selected in each plot. To evaluate the onset of the critical period of weed removal, the plots were left weedy until VE (crop emergence), V2 (two leaves), V4 (four leaves), V6 (six leaves), R1 (floral head initiation) and R5 (beginning of flowering) [23]. At these stages, weeds were removed, and the plots were then kept weed-free for the remainder of the season. The second series of treatments included an increased duration of weed control where plots were maintained weed-free until the VE, V2, V4 V6, R1, and R5 sunflower development stages. The experiment also included weedy and weed-free control treatments. The season-long weed-free plots and the plots with different weed removal treatments were maintained via hand-hoeing. Each plot was 4,2 m wide and 10 m long. Two outer rows of each plot were used as a buffer row, while the data assessment was carried out from two central rows.

2.3. Weed and Crop Measure

Naturally occurring weed populations were utilized in all experimental years. A species' composition was evaluated at the R1 stage of sunflower each year by classifying and counting randomly placed ten 0.5 by 0.5 m quadrats in season-long weedy plots.

To determine the accumulation of weed biomass, aboveground weeds were clipped at VE, V2, V4, V6, R1, R5, and during harvest from four 1 m^2 of each plot to estimate weed biomass accumulation. The weeds were dried at 70 °C to a constant moisture content and expressed in g m^{-1}.

Crop harvest was conducted approximately one to two weeks after physiological maturity on 16 September 2010, 26 September 2011, 20 September 2014, and 19 September 2015. Before harvest, ten consecutive plants were selected from the middle row to determine plant height and head diameter. Samples for grain yield determination were obtained by hand-harvesting the middle two rows for the full length of every plot; these were shelled and adjusted to 11% moisture, weighted for crop yield, and their 1000-kernel weight was calculated. The oil content of sunflower seeds was measured using an MQA 7005 NMR Analyser.

2.4. Data Analysis

Relative abundance values were calculated by plot for each weed species as follows: relative density + relative frequency/2 [24], where relative cover was calculated as the cover of individuals for a given species for each plot divided by the total cover of individuals within the plot. The relative frequency was calculated as the proportion of plots in which the species was present divided by the total frequency of all species. Then, relative abundance values were calculated for each weed species as follows: (relative cover + relative frequency)/2.

The duration periods of competition were correlated with thermal time by calculating the growing degree days (GDD) using minimum and maximum air temperature from a nearby weather station of the State Hydro-meteorological Institute (DHMZ). A base temperature of 6.7 °C was used as the minimum temperature for sunflower growth. The time of crop sowing (days after sowing, DAS) was used as the reference point for the accumulation of GDD and was calculated according to the following equation [25]:

$$GDD = \sum [\{(T_{max} - T_{min})/2\} - T_{base}]$$

where T_{max} and T_{min} are daily maximum and minimum air temperatures (°C) and T_{base} is the base threshold temperature, set at 6.7 °C.

The relationship between the treatments and weed biomass accumulation was described using PROC REG in SAS, version 9.4 [26]. To determine the type of relationship, a Schumacher's model was fitted to the weed-infested treatment and weed biomass accumulation [27]:

$$Y = e^{a+b/x}$$

where Y is the weed dry weight (g m^{-2}), e is a constant, a is the maximum weed biomass, b is the asymptote of the curve and x is the duration of the weed-infested period expressed in growing degree days (GDD).

The four-parameter log-logistic model was used to describe the critical period of weed control (CPWC), which is suitable for describing both the increasing duration of weed interference on relative yield and the increasing length of the weed-free period [28,29]. The relative yield data were analyzed using the following equation:

$$Y = [C + (D - C)]/\{1 + \exp[B(\log X - \log E)]\}$$

where Y is the percentage of season-long weed-free yield; C is the lower limit; D is the upper limit; X is the time (*x*-axis expressed in GDD); E is the inflection point; and B is the slope of the line at the inflection point.

An analysis of variance (ANOVA) was performed using the PROC MIXED procedure in SAS 9.4 [26] to test for the significance ($p < 0.05$) of site, years, treatment combinations, replications, and their interactions based on the increasing duration of weed interference for crop height (cm), head diameter (cm), 1000-kernel weight (g), and seed oil content (%).

3. Results

3.1. Weed Community in Sunflower

A total of thirty-two species of varied perennation were found in the study area, including 1 cryptogam (*Equisetum arvense*), 10 grasses, and 27 dicot species (Table 2). The total species number and relative abundance values were similar between the locations and years, with an overall average of 13.5 for species richness and 95.75 for relative abundance.

Table 2. Weed composition, functional groups and mean relative abundance values measured at the floral head initiation stage of sunflower growing in Valpovo (2010 and 2011) and Darda (2014 and 2015).

Scientific Name	Common Name	Functional Groups		Mean Relative Abundance Value			
		LC	WC	2010 Valpovo	2011 Valpovo	2014 Darda	2015 Darda
Abutilon theophrasti Medik.	Velvetleaf	A	D	-	-	8.2	0.1
Ambrosia artemisiifolia L.	Common ragweed	A	D	25.3	23.1	29.1	19.9
Amaranthus retroflexus L.	Redroot pigweed	A	D	-	-	0.1	1.2
Anagallis arvensis L.	Scarlet pimpernel	A	D	-	-	-	0.1
Arctium lappa L.	Burdock	B	D	-	-	0.2	-
Atriplex patula L.	Spear saltbush	A	D				
Calystegia sepium (L.) R. Br.	Great bindweed	P	D	-	-	7.4	-
Capsella bursa-pastoris (L.) Med.	Sheperd's purse	A	D	-	0.1	-	-
Chenopodium album L.	Common lambsquarters	A	D	13.3	14.1	21.4	18.3

Table 2. *Cont.*

Scientific Name	Common Name	Functional Groups		Mean Relative Abundance Value			
		LC	WC	2010 Valpovo	2011	2014 Darda	2015
Cirsium arvense (L.) Scop.	Creeping thistle	P	D	-	-	-	5.9
Convolvulus arvensis L.	Bindweed	P	D	0.1	-	0.1	4.5
Datura stramonium L.	Jimsonweed	A	D	-	-	6.9	0.1
Daucus carota L.	Wild carrot	B	D	-	-	0.1	-
Digitaria sanquinalis	Hairy crabgrass	A	M				
Echinochloa crus-galli (L.) P. Beauv	Barnyard grass	A	M	16.4	21.2	-	0.1
Equisetum arvense L.	Field horsetail	P	C	-	-	0.1	-
Galinsoga parviflora Cav.	Galant soldier	A	D	5.3	0.1	-	-
Geranium molle L.	Dovefoot geranium	A	D	0.1	-	-	-
Gypsophyla muralis L.	Low baby's breath	A	D	0.1	-	-	-
Matricaria chamomilla L.	Common chamomile	A	D	0.8	1.3	-	-
Plantago major L.	Broad-leaved plantain	P	D	1.3	0.9	-	-
Polygonum aviculare L.	Prostrate knotweed	A	D	0.1	0.1	-	-
Polygonum lapathifolium L.	Pale smartweed	A	D	6.4	5.4	0.1	1.7
Ranunculus repens L.	Creeping buttercup	P	D	0.1	-	-	-
Rorippa austriaca (Crantz) Besser	Austrian fieldcrest	P	D	0.1	-	-	-
Rubus fruticosus L.	European blackberry	P	D	-	-	0.1	-
Rumex crispus L.	Curled dock	P	D	-	-	0.1	-
Setaria viridis (L.) Beauv.	Green foxtail	A	M	12.3	8.3	2.8	-
Solanum nigurm L.	Black nightshade	A	D	-	-	1.2	6.0
Sorghum halepense (L.) Pers.	Johnson grass	P	M	-	-	11.1	4.3
Stachys annua	Annual woundwort	A	D	-	-	-	1.2
Xanthium strumarium L.	Common cocklebur	A	D	-	-	-	3.2
TOTAL number of species				14	10	16	14
TOTAL relative abundance value				95.7	84.3	104.4	92.6

Functional groups: LC—life cycle: P = perennial; A = annual; B = biannual; WC—weed categories: M = monocotyledon; D = dicotyledon; C = cryptogam.

The annual broadleaved weeds *Ambrosia artemisiifolia*, *Chenopodium album*, and *Polygonum lapathifolium* were the dominant species throughout the experiment. The primary grassy species *Echinochloa crus-galli* and *Setaria glauca* were predominant in the first two year of the experiment (location Valpovo), while perennial grass *Sorghum halepense* was abundant in the third year of the experiment (location Darda). Moreover, those weeds, particularly dicots *A. artemisiifolia*, *C. album*, and *P. lapathifolium*, form the main biomass because of their significant size.

3.2. Weed Biomass Accumulation

Total dry weed biomass increased progressively in relation to the increase in the competition duration (Figure 1, Table 3). In the plots left with the weeds for the entire season, the total weed biomass accumulation reached, at harvest, values of 2.258,8 g m^{-2}, 2.325 8 g m^{-2}, 2.737,5 8 g m^{-2}, and 1.779,3 8 g m^{-2}, in 2010, 2011, 2014, and 2015, respectively. The highest weed biomass was determined in 2014 when the highest total number of species and highest total relative abundance were recorded (Table 2). Moreover, robust annual dicots *C. album* and *A. artemisiifolia* and perennial grass species *S. halepense* reached the highest mean relative abundance values and significantly influenced the development of biomass.

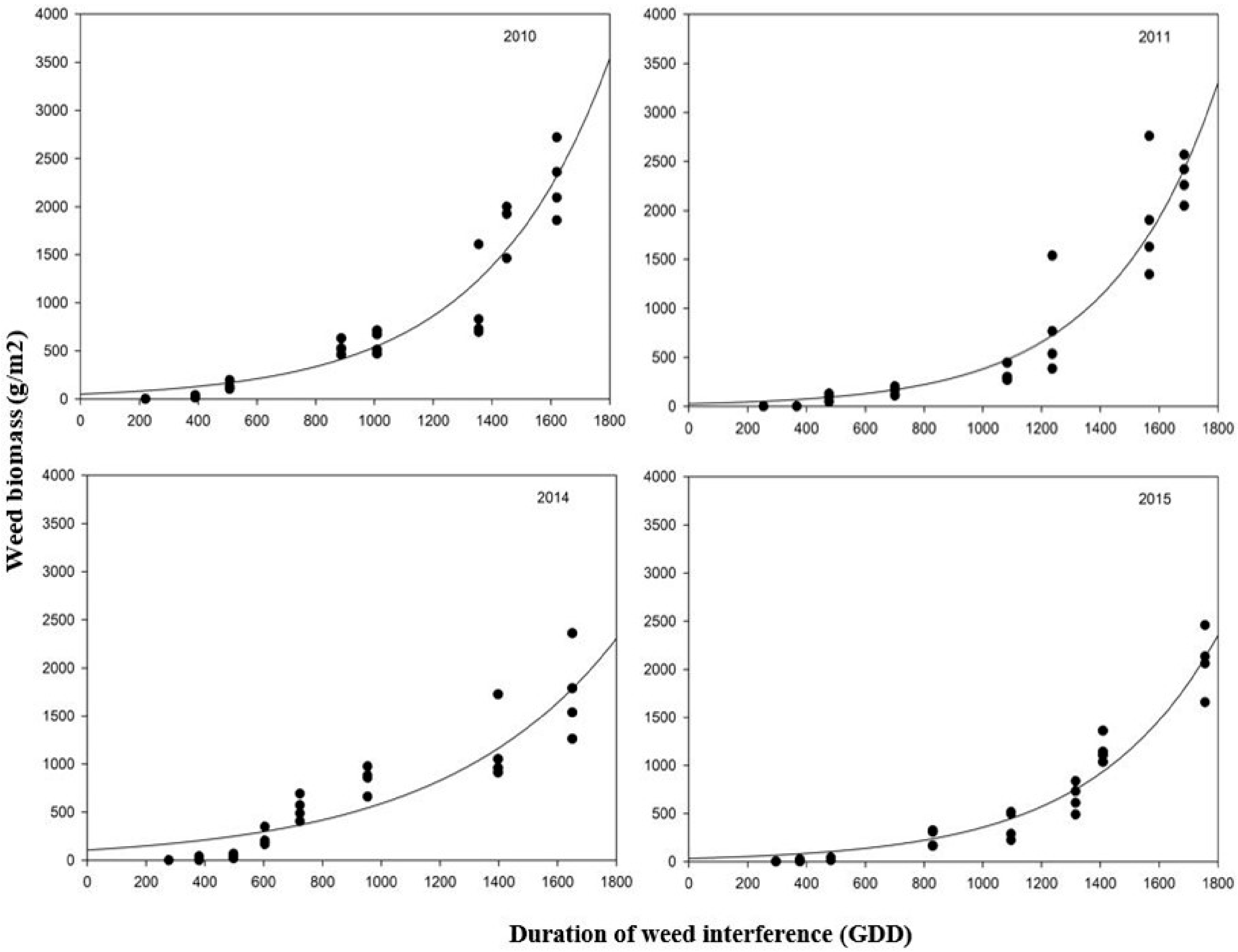

Figure 1. The effect of increasing the duration of weed interference on weed biomass accumulation during the study period in Valpovo (2010 and 2011) and in Darda (2014 and 2015).

Table 3. Parameter value for response curves using Schumacher's model on weed biomass accumulation in the sunflower crop during 2010 and 2011 in Valpovo and 2014 and 2015 in Darda.

Year	Location	a	b	R^2
2010	Valpovo	51.29	0.002352	0.91
2011		25.7	0.002697	0.91
2014	Darda	106.6	0.001708	0.83
2015		33.68	0.002360	0.95

a is the maximum weed biomass, b is the asymptote of the curve, R^2 is the coefficient of determination.

Schumacher's model provided the best fit for weed biomass accumulation for all years and both sites (Figure 1), and the equation parameters are given in Table 3. The weeds reached 10% of their final weight between the V2 and V4 sunflower development stages, but significant growth was observed after accumulating 1000 GDD.

3.3. Critical Period of Weed Removal

There was an interaction between the years and the locations; therefore, the data were assessed separately for each site and year. The season-long weed-free yields were 3286 kg ha^{-1} in 2010 and 2002 kg ha^{-1} in 2011 at Valpovo, and 2893 kg ha^{-1} in 2014 and 2660 kg ha^{-1} in 2015 at Darda. In season-long weedy plots, the sunflower yields were 924 and 763 kg ha^{-1} in 2010 and 2011 in Valpovo and 903 and 886 in 2014 and 2015 in Darda, respectively.

The four-parameter log-logistic model provided the best fit for increasing both the duration of the weed interference and that of the weed-free period (Figure 2), and the equation parameters are given in Table 4. The critical period of weed control varied among the locations and years.

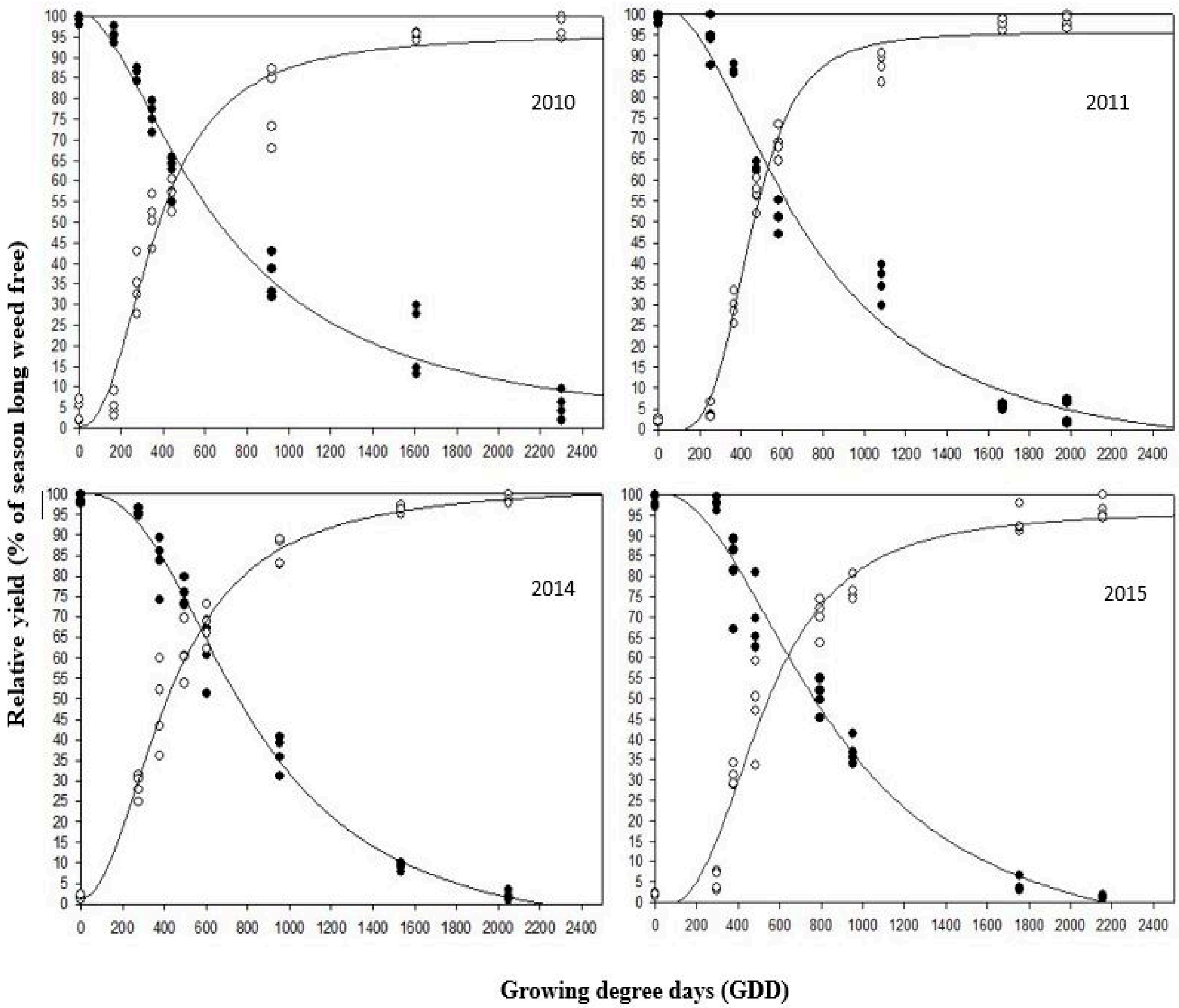

Figure 2. The effect of increasing the duration of weed interference (black circle) and weed-free periods (uncolored circles) on sunflower yield during the study period in Valpovo (2010 and 2011) and in Darda (2014 and 2015).

Using the arbitrary 5% acceptable yield loss, the beginning of the critical period of weed removal in the sunflower crop occurred from 141 to 234 GDD, which corresponded to the V2–V3 crop growth stages across both sites and years (Table 5). This equates to 2–3 weeks after crop emergence. The end of the critical period of weed removal occurred from 1365 to 1932 GDD. This corresponded to the R4–R5 crop growth stages (period from the inflorescence beginning to open and the beginning of flowering) or 12–14 weeks after sunflower emergence.

Table 4. Parameter estimates with standard errors (in parenthesis) according to site–year in the sunflower crop using four-parameter log-logistic model for calculating the critical period of weed removal in Valpovo (2010 and 2011) and in Darda (2014 and 2015).

Year	Duration of Weed Interference				Duration of Weed-Free Period			
	B	C	D	I_{50}	B	C	D	I_{50}
2010	1.8 (0.2)	16.1 (4.3)	100.3 (2.1)	541 (52)	−1.8 (0.2)	18.6 (2.2)	103.2 (3.9)	481 (41)
2011	1.2 (0.2)	1.5 (25.9)	99.5 (2.1)	1236 (512)	−1.8 (0.2)	19.1 (2.3)	97.3 (3.0)	330 (23)
2014	1.6 (0.2)	13.6 (9.4)	101.6 (2.1)	761 (137)	−2.7 (0.3)	32.6 (2.3)	97.4 (1.7)	313 (16)
2015	1.7 (0.2)	12.9 (7.4)	101.0 (2.0)	760 (106)	−2.4 (0.3)	23.7 (2.4)	98.3 (2.2)	385 (20)

B is the slope of the line at the inflection point; C is the lower limit; D is the upper limit; I_{50} is the GDD giving a 50% response between the upper and lower limits (inflection point).

Table 5. The critical period of weed control (CPWC) for the sunflower crop based on 5% and 10% acceptable yield loss.

Acceptable Yield Loss (%)	Year	Beginning of the CWPC			End of CWPC		
		GDD (±SE)	CGS	DAE	GDD (±SE)	CGS	DAE
5%	2010	141 (16.7)	V2	14	1860 (636.8)	R5	98
	2011	191 (19.4)	V2	17	1365 (412.2)	R4	84
	2014	234 (19.4)	V3	25	1435 (133.4)	R4	82
	2015	208 (20.8)	V3	21	1932 (227.0)	R5	92
10%	2010	198 (18.2)	V4	27	1377 (344.6)	R4	76
	2011	237 (36.6)	V5	30	1003 (218.6)	R3	69
	2014	301 (22.0)	V7	36	1151 (79.9)	R3	72
	2015	291 (23.3)	V6	32	1432 (131.4)	R4	79

GDD (growing degree days); CGS (crop growth stage); DAE (days after emergence).

Based on a 10% yield loss level, the beginning of the critical period of weed removal ranged from 198 to 301 GDD, approximately 4–5 weeks after the crop emergence or when the sunflower developed 4–6 leaves. The end time for the critical period of weed control for the sunflower crop was calculated as 1003 to 1432 GDD, corresponding to approximately 10–11 weeks after the crop emergence, when inflorescence began to open.

3.4. Influence of Weed Interference on Yield Components and Oilseed Content

The yield components of sunflower (Table 6, Figure 3) varied between the years and locations. Increasing the duration of weed interference negatively affected the crop height, head diameter, and 1000-kernel weight, but not the seed oil content. Overall, the lowest crop height, head diameter, and 1000-kernel weight were recorded in the second year of the experiment (2011) in Valpovo.

The effect of weed removal time showed a significant difference in crop height (cm), head diameter (cm), and 1000-kernel weight, but not in seed oil content. A significantly lower height of the sunflower plants was recorded in plots left unweeded during the whole season. Moreover, allowing weeds to grow after V2 (2010 and 2015) or even after VE (2011 and 2014) can result in lower plant height. Head diameter followed the same pattern, and significantly decreased in size if the weeds were present after the VE (2010, 2014, and 2015) or V2 (2011) crop growth stages. Additionally, after the same periods, VE (2010, 2011, and 2014) and V2 (2015) significantly decreased the 1000-kernel weight due to competition with the weeds. The seed oil content (%) was the only aspect that did not show a significant difference related to the duration of weed interference.

Table 6. ANOVA for the effect of the critical period of weed removal on crop height (cm), head diameter (cm), 1000-kernel weight (g), and oil content (%).

Variable	df	Crop Height (cm)		Head Diameter (cm)		1000-Kernel Weight (g)		Seed Oil Content (%)	
		MSS	P > F	MSS	P > F	MSS	P > F	MSS	P > F
Location (Loc)	1	169.050	0.363	1115.750	0.695	943.951	0.052	943.951	0.052
Year (Yr)	1	12.375	0.746	4214.882	0.495	44.959	0.218	44.959	0.332
Weed removal (WR)	7	40.712	0.006 **	793.296	0.034 **	13.046	0.001 **	9.550	0.110
Loc × Yr	1	69.473	0.001 **	4121.072	0.000 ***	6.426	0.019 *	6.426	0.286
Loc × WR	7	12.655	0.020 **	320.514	0.086	11.116	0.001 **	7.903	0.264
WR × Yr	7	4.955	0.168	180.065	0.255	0.986	0.329	3.582	0.646
Loc × Yr × WR	7	2.312	0.670	107.098	0.087	0.696	0.970	4.808	0.107
Error	96	3.290		57.990		2.753		2.753	

p = 0.01–0.05 *; p = 0.001–0.01 **; p = 0.0001–0.001 ***.

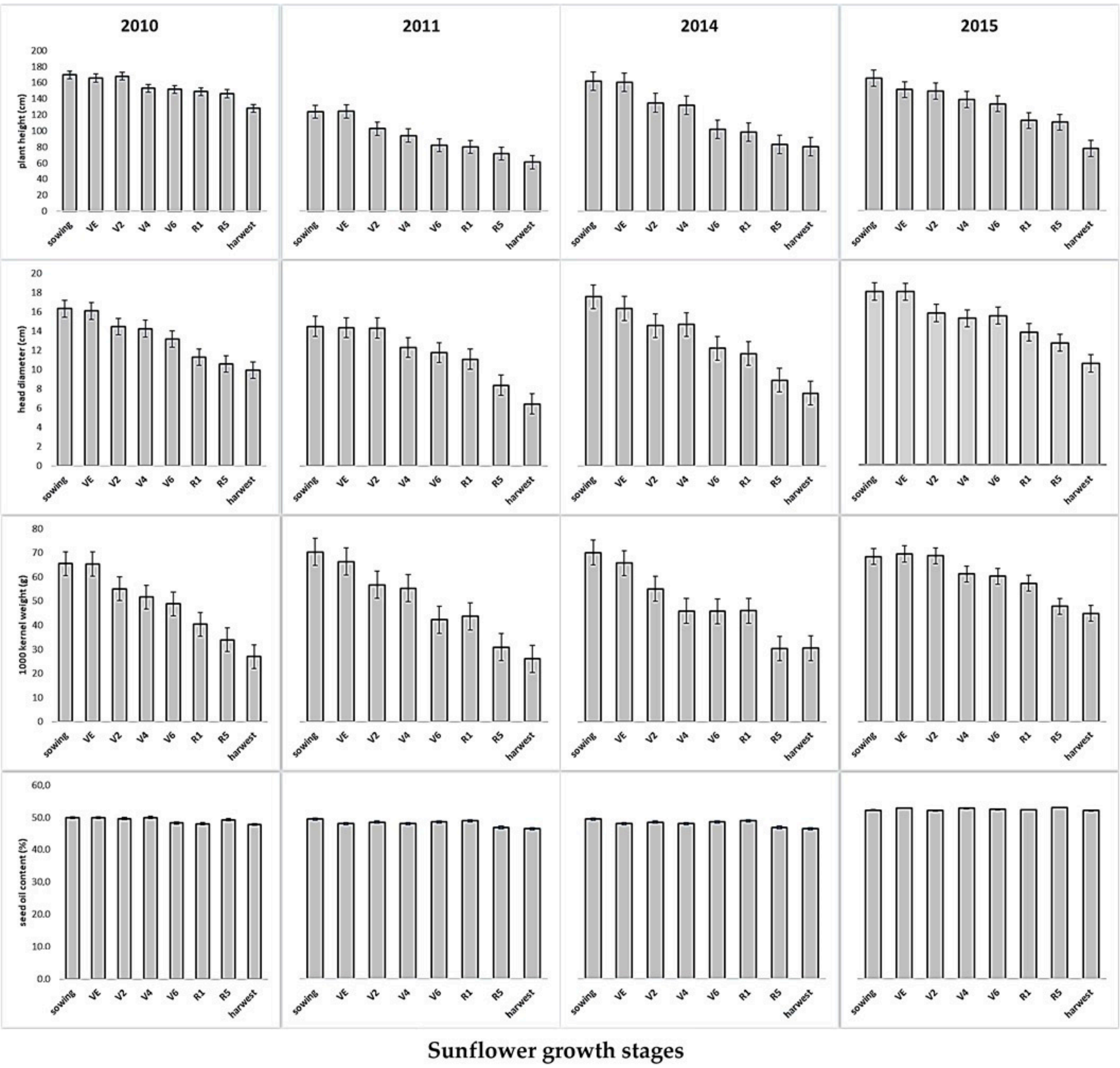

Figure 3. Mean comparison of effects of different periods of weed interference in sunflower regarding plant height (cm), head diameter (cm), 1000-kernel weight (g), and seed oil content (%) growing in Valpovo (2010 and 2011) and Darda (2014 and 2015).

4. Discussion

A weed community composed of varying species, density, and relative abundance was observed during the experimental period (Table 2), which was typical of weed flora in row crop fields of this region [30]. In the present study, the variability in the weed density among the years and among the locations is likely due to location differences in weed seed banks, soil types, and rainfall patterns [9,31].

Interference from the multispecific weed community affected the sunflower yield differently depending on the duration and period of infestation, and on environmental factors. The large broad-leaved weeds, *Ambrosia artemisiifolia*, *Chenopodium album*, and *Polygonum lapathifolium*, that dominated throughout the experiment had the greatest effect on the crop, significantly suppressing the yield when not controlled. Vigorous sunflower competition with these predominant weed species has also been reported [31–33]. These robust weeds represent a significant problem in sunflower production because compared to other row crops, the growers still have a limited range or deficiency of adequate herbicides available to control broadleaved weeds [6,34]. Additionally, they germinate almost simultaneously as sunflowers and put this crop under pressure [35].

Weed biomass significantly increased during the weed-infested period. This is in agreement with many research results where robust summer dicot species like *A. artemisiifolia*, *C. album*, *Polygonum* spp. dominate throughout the experiments [6,36,37]. Moreover, those weeds uptake a larger amount of nutrients at the early stages of sunflower development [38], which is reflected in their competition with crops.

Yield loss due to weed competition depends on the composition of weed species, population density, and the relative time of their emergence [39]. Crop yield and yield components generally decreased with an increased duration of weed interference [31,32]. The determination of weed interference and duration of competition can help growers to improve the cost effectiveness and efficacy of their weed management program [40].

The critical period of weed competition has been studied worldwide in various crops and environmental conditions [13,31,32]. This is a concept that relates the yield reduction caused by weed competition to an economic threshold [12], and the length of the critical period for weed control increases with increasing weed density. In highly infested fields, the concept of the critical period for weed control has several weaknesses [12] since it is assumed that weeds are equally easy to control at all growth stages in a required time and that weeds have no negative impacts except on crop yield.

The onset of the critical period in sunflower, based on a 5% acceptable yield loss, ranged in this research from 141 to 234 GDD, while for a 10% acceptable yield loss, the beginning of this period ranged from 198 to 301 GDD. This is in line with several other studies where the beginning of the critical period of weed removal for a 5% acceptable yield loss started between the V3 and V4 stages of sunflower growing without the application of pre-emergence herbicides, or at the V7 and V8 stages when pre-emergence herbicides were applied [31]. The use of pre-emergence herbicides, as shown in the abovementioned research, could extend post-herbicide treatments by another 6–12 days. By waiting for this period without the pre-emergence application of herbicides, weeds could continue the competition and decrease the sunflower yield by 10%, as shown in this study. However, in the case of conventional herbicide programs (not IMI-resistant sunflowers), post-emergence herbicide treatments should be applied up to 4 weeks after crop emergence [31].

The duration of the critical period of weed removal in this study varied among the years and locations and was determined to be between the 2nd and 3rd, and the 12th and 14th weeks to achieve an accepTable 5% yield loss. In other experiments [9,10,14,31], the duration of time of weed presence was also not stable among sites and years, which can lead to the same general conclusion that this might be due to various levels of several weed interferences that were present across the years and locations.

The presence of weeds more than 3 weeks after crop emergence influences the growth of sunflower and the yield components. This finding also agrees with those of previous studies [32,41]. These highlighted the importance of early weed management that allows for a better sunflower growth and productivity. Plant height, head diameter, and 1000-kernel weight decreased significantly with an increasing duration of weed interference. Others also reported that those yield components are most affected by various biotic and abiotic stresses, resulting in yield loss [42–44].

In contrast, the percentage of oil content in this research was not affected by the presence of weeds. This could be attributed to the fact that the oil content in the sunflower crop is mainly affected by the hybrid [45,46].

5. Conclusions

The results of the present study revealed that even a small delay in weed control in the sunflower crop can cause a significant yield loss. The abundant large broad-leaved weeds *Ambrosia artemisiifolia*, *Chenopodium album*, and *Polygonum lapathifolium* were capable of developing significant aboveground biomass and compete with the crop even at the early stages of development. Based on a 5% acceptable yield loss, the beginning of the critical period of weed removal ranged from 141 to 234 GDD, which corresponded to the V2–V3 crop growth stages. The sunflower crop has to be kept weed-free until the R4–R5 growth stages or from 1365 to 1932 GDD, a period when the inflorescence begins to open and flowering begins. The sunflower yield and yield components varied between the years and among locations. Increasing the duration of weed interference negatively affected crop height, head diameter, and 1000-kernel weight, but not the seed oil content.

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