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Critical Time for Weed Removal in Corn as Influenced by Planting Pattern and PRE Herbicides

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Abstract: Determining the critical time for weed removal (CTWR) is essential for the development of an integrated weed management plan. Therefore, field experiments were conducted to evaluate the effects of two planting patterns (standard and twin-row) with and without PRE-applied herbicides on CTWR in corn. Experiments were laid out in a split-plot arrangement with two main plots: (i) standard row planting (SRP) that is 70 cm wide, and (ii) twin-row planting (TRP) with 50 cm distance between each set of double rows. Each main plot was divided into two sub-plots (with and without PRE herbicides). The sub-sub-plots consisted of seven weed removal timings for PRE herbicides, and tank mixes were utilized (S-metolachlor (1.44 kg a.i. ha^{-1}) + terbutylazine (0.75 kg a.i. ha^{-1})). The CTWR without PRE herbicides was similar in both the SRP and TRP systems, where it was around the V1 to V2 (16 to 19 d after emergence (DAE)) growth stages. The use of PRE-applied herbicides delayed CTWR in SRP to the V4 to V10 (25 to 58 DAE) stages and up to the V11 (60 DAE) stage in TRP. These results clearly indicate that PRE herbicides are important for protecting corn yields regardless of the planting pattern. In more meteorologically favorable seasons (sufficient heat and precipitation) in both sowing systems, corn plants produce their biological maximum with the fact that over the number of plants per unit area (SRP = 80,000 plants ha^{-1}, TRP = 93,900 plants ha^{-1}) provide higher yields in variants with PRE herbicides, and thus the advantage of the TRP system can be justified.

Keywords: corn; CTWC; planting pattern; crop density; grain yield; PRE herbicides

Citation: Nedeljković, D.; Knežević, S.; Božić, D.; Vrbničanin, S. Critical Time for Weed Removal in Corn as Influenced by Planting Pattern and PRE Herbicides. *Agriculture* **2021**, *11*, 587. https://doi.org/10.3390/agriculture11070587

Academic Editor: Luis Antonio de Avila

Received: 11 May 2021
Accepted: 21 June 2021
Published: 24 June 2021

1. Introduction

Corn (*Zea mays* L.) is one of the most important crops grown worldwide in a wide range of environments because of its greater adaptability [1]. Among cereal crops, corn has the highest average yield per hectare and remains third after wheat and rice in total land area worldwide [2,3]. Corn is one of the leading crops in Serbia, grown on more than 1 million ha [4,5]. One of the most important goals in corn production is to protect yield; however, this is not always easy due to many factors. Besides other factors, yield losses in corn can be highly impacted by competition from weeds [6–8] to as much as 90%. The level of weed competition depends on the environmental conditions, soil properties, and weed abundance [9–13]. The competitiveness of weeds is often measured in terms of crop yield reduction per unit of weed population or biomass, and the yield reduction can also be influenced by the spectrum of weed species [14,15]. Harrison et al. [16] reported a 13.6% yield loss in corn from a moderate weed density (1 plant 10 m^{-2}), compared to 90% yield loss from higher weed densities. Other studies reported that 6 to 12 plants m^{-2} of *Xanthium strumarium* reduced corn yields by 28 to 45% [17–19]. Corn competitiveness can be also improved by adjusting production practices such as reducing the row spacing, increasing the planting density, and planting more competitive cultivars that exhibit weed-suppressive potential [20].

Determining the critical period of weed control (CPWC) could be a very helpful tool in the integrated weed management toolbox. By definition, the CPWC is a period in the crop growth cycle during which weeds must be controlled to prevent yield losses. Knowing the CPWC is useful in making decisions on the need for and timing of weed control. Knezevic et al. [21] described the CPWC as the time interval between two separately measured crop–weed competition components: (1) the critical timing of weed removal (CTWR) or the maximum amount of time early-season weed competition can be tolerated by the crop before the crop becomes subject to an irrevocable yield reduction, and (2) the critical weed-free period (CWFP) or the minimum weed-free period required from the time of crop planting to prevent unacceptable yield reductions. The CTWR is estimated to determine the "beginning" of the CPWC, while the CWFP determines its "end". Results from both components are combined to determine the CPWC. Theoretically, weed control before and after the CPWC does not contribute to the conservation of crop yield potential.

A significant number of studies have been conducted around the world to determine the CPWC in various crops including corn, with a range of environmental conditions [22–30]. The CPWC in corn in Germany starts around the four- or six-leaf stage and ends at tassel emergence [31]. Hall et al. [23] determined the CPWC between three- and fourteen-leaf stages. Bedmar et al. [32] reported CPWC based upon an arbitrary 2.5% level of yield loss, which varies between five and seven leaves of corn. The beginning of CPWC (or the CTWR) in no-till corn in Canada was relatively stable (six-leaf stage of corn), while the end of CPWC (or the CWFP) varied from the nine- to thirteen-leaf stages [24]. At 10% relative yield loss, the CTWR ranged between the two- and six-leaf stages, and the CWFP between the twelve-leaf stage and two weeks after tasseling [33]. CTWR in Italy was calculated as being from 68 to 182 GDD (V1–V7 leaf stages) in 1992 and from 201 to 345 GDD (V7–V10 leaf stages) in 1993, at the arbitrary 5% yield loss level [34]. Knezevic et al. [35] reported that without a PRE herbicide, CTWR started at the three-leaf stage, while with a PRE application of atrazine, the CTWR was delayed to the five-leaf stage. PRE application of Acuron® (bicyclopyrone (0.0349 kg ha^{-1}) + mesotrione (0.13994 kg ha^{-1}) + S-metolachlor (1.262 kg ha^{-1}) + atrazine (0.589 kg ha^{-1})) further delayed the CTWR to the ten-leaf stage, which was close to the time of corn canopy closure.

Since all studies in different regions showed various results for CTWR, it is necessary to determine CTWR for a particular region by considering local weed species compositions, and climate. In addition, there are no data about the impact of planting system production such as the effect of row spacing, planting density, and type of cultivars on CTWR in corn. Knezevic et al. [36] reported that soybeans planted in a narrow row spacing were more competitive. In particular, when comparing three row spacings (19, 38, and 76 cm) in soybeans, Knezevic reported that the earliest CTWR occurred in the 76-cm rows, and the latest CTWR occurred in the 19-cm rows. Hock et al. [37] also found that weeds grown with soybean planted in 19-cm rows produced less total dry matter, had a lower plant volume, and had a reduced soybean yield less than weed species grown in 76-cm rows. Therefore, the objective of this study was to evaluate the effects of two planting patterns (SRP and TRP) with and without PRE-applied herbicides on CTWR in corn.

2. Materials and Methods

2.1. Experimental Site Description

The field experiments were conducted during 2015 (45°09′171′′ N, 20°73′936′′ E), 2016 (45°125′322′′ N, 20°693′786′′ E), and 2017 (45°12′1260′′ N, 20°66′9607′′ E) in the Southern Banat area (northeastern Serbia). Soil type at the location was silty clay loam (Table 1). The chemical properties ranged from moderately alkaline reactions (pH 7.18 to 8.2) to medium supply humus (2.74–3.85%). Before planting, fields were conventionally tilled and disked. Corn was seeded at a depth of 6 cm and planted in 70-cm rows (standard planting) and twin rows (20 cm between 2 rows to then 50 cm distance between each set of double rows). Dates of plantings ranged from 11 April to 29 April depending on the year. The size of each experimental unit was 42 m^2 (10 × 4.2 m), with six crop rows or twin rows in each experimental unit. The seeding rate was 80,000 seed ha^{-1} in the standard system, and 93,900 seeds ha^{-1} in the twin-row planting system production.

Table 1. Chemical properties of soil.

Year	pH in H_2O	pH in KCl	$CaCO_3$ %	N Total %	Humus %	K_2O mg/100 g	P_2O_5 mg/100 g
2015	7.18	6.01	0.95	0.19	3.85	22.1	31.5
2016	8.19	7.69	0.93	0.19	3.31	16.2	34.2
2017	8.20	7.60	6.71	0.17	2.74	30.0	36.1

2.2. Experimental Design

This study was arranged in a split-plot design with three replications. There were two main plots which included: (i) standard row planting (SRP) and (ii) twin-row planting (TRP). Each main plot was divided into two sub-plots, one with PRE herbicide (S-metolachlor (1.44 kg a.i. ha^{-1}) + terbutylazine (0.75 kg a.i. ha^{-1})) application, and one without PRE herbicide application. S-Metolachlor is a selective herbicide used for control of some broadleaf and annual grassy weeds in a wide range of crops such as peanut, cotton, soybean, maize, and tomato [38–40], and terbutylazine is used to control broad-leaved weeds [41]. In Serbia, a major weed problem in corn fields in the Banat area is herbicide-resistant populations of *Sorghum helepense* that are resistant to ALS-inhibiting herbicides, and some broadleaf weeds [42]. For each sub-plot, there were seven sub-sub-plots (experimental units), of which five treatments had weeds growing until the corn development stage: three leaves (V3), six leaves (V6), nine leaves (V9), fifteen leaves (V15), beginning of flowering (VT), and season-long weed-free and season-long weedy plots. The weeds were removed as needed by hand hoeing. Corn growth stage was determined by counting fully developed leaves (collar visible) from 10 consecutive plants in each plot. The use of crop growth stage allowed the determination of the CTWR on the basis of the phonological development of the crop. Average monthly air temperature and total rainfall varied among years (Table 2). PRE herbicide was applied soon after corn planting but prior to crop emergence, using an Amazone UF 1201 sprayer equipped with TeeJet XR 11,003 flat-fan nozzles (Spraying System Co., Wheaton, IL, USA), calibrated to deliver 300 L ha^{-1} solutions at 200 kPa.

Table 2. Average air temperature and total precipitation during 2015 to 2017 growing seasons (April to September) in South Banat district, Serbia.

Month	Temperature °C						Total Precipitation (mm)		
	2015 Min	2015 Max	2016 Min	2016 Max	2017 Min	2017 Max	2015	2016	2017
April	5.2	20.8	15.6	25.5	11.3	20.8	5.1	76.1	3.0
May	16.5	29.6	14.4	24.8	14.2	23.9	63.9	88.7	125.9
June	16.6	29.0	18.0	28.8	19.4	29.6	43.5	117.3	94.1
July	19.1	32.0	18.1	29.2	19.6	31.4	7.0	123.5	43.0
August	18.4	31.8	17.2	28.4	19.7	32.7	82.5	87.6	32.1
September	15.9	26.3	17.1	29.9	16.4	28.0	79.1	33.2	37.9

2.3. Growing Degree Days (GDDs) Calculation

Determination of the CTWR was based on 5% yield loss level assuming: (a) a 5% acceptable yield loss level acceptable by producers; (b) reliable detection of treatment effects despite natural variability in yields with field experimentations; and (c) statistical significance at the 95% level. The growing degree days (GDDs) estimate corresponded to the 95% relative yield for each site–year combination and then related to the corresponding crop growth stage. Air GDDs were used as the explanatory variable and calculated using the method described in [43]. The day after corn emergence (DAE) was used as the reference point for the accumulation of GDDs. Temperature was recorded hourly with temperature data loggers throughout the growing season and was converted to GDDs using the following equation [43]:

$$\text{GDD} = \sum [(\text{Tmax} + \text{Tmin})/2 - \text{Tbase}] \quad (1)$$

where Tmax and Tmin are daily maximum and minimum air temperatures (°C), and Tbase is the base temperature (10 °C) for corn growth.

2.4. Data Collection

There was no irrigation applied on the experimental plots in the trial, and temperature and rainfall data during the corn growing seasons were obtained from a local meteorological service (Table 2). The total rainfall during the 2015, 2016, and 2017 growing seasons at the experimental site was 281.1, 526.4, and 336.0 mm, respectively.

Experiments were performed at different locations each year and under local weed populations. To describe the early-season competitive environment at each site, species composition, mean weed density, and height for each species were measured in the season-long weedy plots. Additionally, species composition and weed density were also assessed in all plots before every weed removal (data not shown). Weed infestations were evaluated at the completion of each treatment by identifying and counting weed plants from two 0.25 m^2 quadrats placed within 2 m from the top and bottom edges of the plot. Above-ground weed biomass was harvested in all treatments and in season-long weedy plots. Weeds were cut at ground level in each quadrat (Table 3), freshly weighed, and then dried at 80 °C until constant weight, and total dry weights from all species were measured. The final corn harvest was conducted soon after physiological maturity by hand-harvesting the middle two rows (third and fourth rows), each 6 m long in every plot and shelled, and seed moisture was adjusted to 14% moisture.

Table 3. The population density (average plants m^{-2}) of weed species in the experimental area in season-long weed treatment at VT stage (tasseling) of corn.

Weed Species	SRP [b] 2015		TRP 2015		SRP 2016		TRP 2016		SRP 2017		TRP 2017	
PRE	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without
Common sunflower (*Helianthus annuus*)	5.7 (7.6%) [a]	6.0 (6.9%)	4.7 (7.6%)	5.6 (7.2%)	2.7 (6.8%)	2.0 (1.4%)	2.6 (7.5%)	2.0 (1.6%)	3.6 (7.7%)	3.0 (2.4%)	2.7 (6.5%)	5.7 (4.8%)
Creeping thistle (*Cirsium arvense*)	1.0 (1.3%)	3.0 (3.5%)	2.0 (3.2%)	1.0 (1.3%)	2.7 (6.8%)	-	1.7 (4.9%)	6.0 (4.7%)	-	-	-	-
Johnson grass (*Sorghum halepense*)	32.3 (42.8%)	35.4 (40.9%)	30.0 (48.6%)	32.6 (41.2%)	13.0 (33.1%)	101.5 (70.8%)	9.7 (28.1%)	61.0 (48.3%)	25.0 (52.8%)	79.3 (63.5%)	16.0 (39.3%)	62.7 (53.3%)
Jimsonweed (*Datura stramonium*)	- [c]	2.5 (2.9%)	4.0 (6.5%)	5.0 (6.3%)	1.3 (3.5%)	4.0 (2.8)	2.5 (7.2%)	4.7 (3.7%)	3.7 (7.7)	3.3 (2.7%)	3.6 (8.8%)	-
Field bindweed (*Convolvulus arvensis*)	-	-	4.0 (6.5%)	-	-	-	-	-	-	-	-	-
Redroot pigweed (*Amaranthus retroflexus*)	19.0 (25.2%)	35.2 (35.2%)	7.3 (11.9%)	22.9 (29.0%)	10.4 (26.4%)	21.3 (14.9%)	8.5 (24.6%)	25.3 (20.1%)	2.6 (5.6%)	13.3 (10.7%)	9.0 (22.1%)	28.3 (24.1%)
Pigweed (*Chenopodium album*)	12.4 (16.4%)	6.3 (7.3%)	6.6 (10.8%)	6.2 (7.8%)	3.0 (7.6%)	5.3 (3.7%)	1.0 (2.9%)	12.3 (9.8%)	5.7 (12.1%)	19.0 (15.2%)	4.0 (9.8%)	12.0 (10.2%)
Black nightshade (*Solanum nigrum*)	5.0 (6.6%)	2.9 (3.3%)	3.0 (4.9%)	5.6 (7.2%)	4.0 (10.2%)	2.5 (1.7%)	2.5 (7.2%)	6.0 (4.7%)	-	1.0 (0.8%)	-	1.0 (0.8%)
Volunteer rapeseed (*Brassica napus*)	-	-	-	-	2.3 (5.8%)	6.7 (4.7%)	6.0 (17.4%)	9.0 (7.1%)	4.0 (8.5%)	3.8 (3.1%)	4.4 (10.8%)	5.0 (4.2%)
Rough cocklebur (*Xanthium strumarium*)	-	-	-	-	-	-	-	-	2.7 (5.6%)	2.0 (1.6%)	1.0 (2,5%)	3.0 (2.5%)
Total weed density (plants m^2)	75.4	86.6	61.7	79.1	39.3	143.3	34.5	126.3	47.3	124.8	40.7	117.7

[a] Figures in parentheses represent percentage of total weed density. [b] Abbreviations: SRP is standard planting pattern; TRP is twin-row planting pattern. [c] Zero weed species.

2.5. Statistical Analysis

In order to determine CTWR, yield data of individual plots were calculated as the percentage (relative yield) of their corresponding weed-free plot yields. The difference between the parameters for each combination of site–year and herbicide applications was also determined by comparing the standard errors (±SE) and t- and F-test at the 5% significance level. All statistical analyses were performed in the R program [44] utilizing the "drc" statistical add-on package [45]. Relative yields where analyzed using the four-parameter log-logistic model, where the D term was fixed at 100 [46]:

$$Y = C + (D - C)/\{1 + \exp[B(\log X - \log E)]\} \quad (2)$$

where Y is the relative yield (percentage of season-long weed-free yield), C is the lower limit, D is the upper limit, X is the GDD calculated after corn emergence, E is the GDD giving a 50% response between the upper and lower limits (ED50), and B is the slope of the line at the inflection point.

3. Results

3.1. Weed Density and Species Composition

Weed species composition and density were monitored in both planting patterns throughout all three years. Therefore, during the first year (2015), which was characterized by a dry season (Table 2), broadleaf weeds were the dominant species. In sub-plots with PRE herbicides, broadleaf weeds accounted for 57.2% in SRP and 51.4% in TRP, compared to grassy weeds (42.8 and 48.6%). In 2016, there were the same trends as in the previous season, where broadleaf weeds were the dominant species with 66.9 and 71.9% in SRP and TRP (33.1 and 28.1%, grassy weeds). In 2017, grassy weeds were the dominant species in SRP, with 52.8% (47.2% broadleaf weeds), while 60.7% of broadleaf weeds (39.3% grassy weeds) were dominant in TRP (Table 3).

Sub-plots without PRE herbicides during 2015 (e.g., dry year) had broadleaf weeds at a similar level (50% share) in both planting patterns to plots with PRE herbicides (Table 3). In wetter years (2016 and 2017), grassy weeds were more dominant than broadleaf weeds. For example, in 2016, the SRP had 70.8% grassy weeds (29.1% broadleaf weeds), compared to 48.3% (51.7% broadleaf weeds) in TRP. Similarly, in 2017, grassy weeds were dominant, with 63.5 and 53.3% in both planting patterns (Table 3).

The total weed density in 2015 in SRP without PRE herbicides was 86.6 plants m^{-2}, compared to 75.4 plants m^{-2} in plots with PRE herbicides, and similar trends were observed in all other years (Figure 1, Table 4).

The five dominant species in all treatments in SRP during 2015 were *Sorghum halepense* (42.8% of the total weed population), *Amaranthus retroflexus*, *Chenopodium album*, *Helianthus annuus*, and *Cirsium arvense*. During 2016, *S. halepense* was predominant with 70.8%, as well as *A. retroflexus*, *C. album*, *Brassica napus*, and *Datura stramonium*. A similar trend was evident in 2017, where *S. halepense* participated with 63.5% of the total weed population (Table 3).

The highest weed density of about 143 plants m^{-2} was counted in SRP in both years in sub-plots without PRE herbicides. However, a significantly lower weed density of about 39 plants m^{-2} was counted in a sub-plot with PRE herbicides (Figure 1, Table 4).

In the twin-row planting pattern, the most dominant weed species in 2015 in the treatment without PRE herbicides were *S. halepense* (41.3%), *A. retroflexus* (29.0%), and *C. album* (7.8%). In the same treatment, the total weed population was 79.1 plant m^{-2}, which is higher than with PRE herbicides, which was 61.7 plant m^{-2}. During 2016 and 2017, in the twin-row planting pattern without PRE, those three weed species kept a dominant place in the total weed population, but in 2016, the total weed density was 126.3 plants m^{-2}, which is 37.4% and 6.8% higher than in 2015 and in 2017, respectively. The lowest total weed density (34.5 plants m^{-2}) was confirmed in the PRE treatment in 2016 compared to without PRE treatment, as well as in relation to both variants (with and without treatment) in 2015 and 2017 (Table 3).

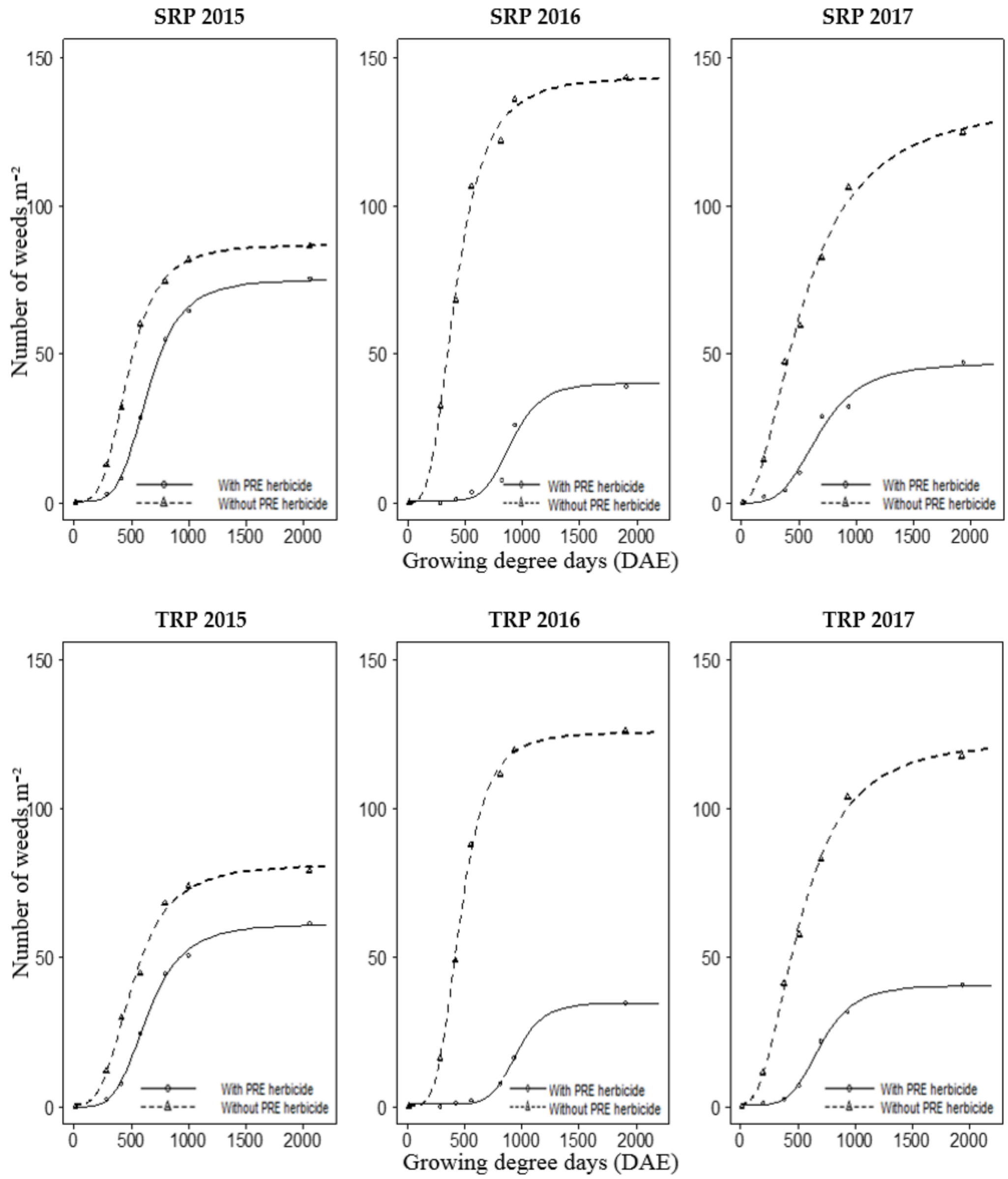

Figure 1. Total weed density response to increasing duration of weed interference as represented by growing degree days (d after emergence, DAE) grown without and with PRE herbicides in standard (SRP) and twin-row (TRP) planting patterns, at Padina, Serbia, 2015–2017.

Generally, the highest weed density (143.3 weds m^{-2}) in 2016 was in both planting patterns in sub-plots without PRE herbicides with a species composition that included: *S. halepense*, *A. retroflexus*, *C. album*, *H. annuus*, *Solanum nigrum*, *B. napus*, D. stramonium, and *C. arvense*. Weeds surveyed during the wet season were higher than in the dry season in terms of weed composition, density, and fresh and dry weights. Additionally, the highest weed density was observed in the vegetative stage compared to the reproductive stage of the crop. However, the wet season in both planting patterns with PRE herbicides recorded the lowest total weed density with a low biomass of weeds as a consequence of the PRE herbicide reaction. In addition, the twin-row planting pattern has a positive impact on the suppression of the weed density and composition if it is compared with standard row planting.

Table 4. Regression parameters showing the slope (B), lower limit (C), upper limit (D), and GDD at 50% reduction (I50) number of plants m^{-2} (weeds) at two different planting patterns (standard and twin-row planting patterns) at two levels of herbicide application (with and without PRE herbicide) in corn in a field experiment conducted at Padina, Serbia, from 2015 to 2017.

Year	Planting Pattern	Herbicide Application	Regression Parameters (±SE)			
			B	C	D	I50
2015	SRP	With PRE	−4.5 (0.3)	0.3 (1.1)	75.1 (1.5)	644.9 (12.1)
		Without PRE	−3.6 (0.3)	0.4 (1.5)	66.9 (1.8)	472.3 (10.3)
	TPR	With PRE	−4.1 (0.4)	0.1 (1.3)	61.4 (1.9)	642.9 (19.0)
		Without PRE	−3.2 (0.4)	0.6 (3.1)	81.5 (3.2)	510.9 (27.4)
2016	SRP	With PRE	−7.0 (0.8)	−0.5 (1.6)	40.3 (3.2)	905.3 (37.8)
		Without PRE	−3.2 (0.5)	−0.1 (5.1)	143.8 (5.0)	419.4 (19.8)
	TRP	With PRE	−8.2 (1.5)	0.6 (0.5)	34.7 (0.9)	953.1 (15.8)
		Without PRE	−4.1 (0.3)	−0.2 (2.3)	125.8 (2.2)	460.4 (9.4)
2017	SRP	With PRE	−3.6 (1.1)	−0.04 (2.5)	47.3 (4.8)	683.1 (64.9)
		Without PRE	−2.0 (0.3)	−0.1 (4.2)	135.8 (7.9)	543.3 (42.7)
	TRP	With PRE	−4.8 (0.5)	−0.3 (0.7)	40.7 (1.1)	697.6 (16.5)
		Without PRE	−2.5 (0.3)	−0.8 (3.1)	123.8 (4.6)	519.7 (24.7)

3.2. Corn Yield

Yields (Figure 2) of corn were variable among planting systems, years, and locations. Generally, an increasing duration of weed interference reduced corn yields in both planting patterns. Additionally, the effects on yield were greater in plots without PRE herbicide application compared to the plots with PRE herbicide application regardless of planting patterns. Generally, yields of corn in the season-long weedy and weed-free plots were the lowest and highest, respectively. Weed-free plots in 2015 yielded 9045 and 8807 kg ha^{-1} at SRP with and without PRE herbicides, respectively. Similarly, corn in the TRP system yielded 8133 and 7752 kg ha^{-1} (upper limit of the curve, Figure 2).

Corn yield in the season-long weedy plots without PRE herbicide application in 2015 was 517 (SRP) and 413 kg ha^{-1} (TRP), compared to 550 (SRP) and 777 kg ha^{-1} (TRP) (lower limit of the curve, Figure 2) with PRE herbicides. Similar trends were observed across all years (Figure 2).

3.3. Corn Yield Losses

Corn yield losses across all locations and years were always higher in the plots without PRE herbicide application than with PRE herbicide application, and there were also some small differences between planting patterns.

In 2015, corn yield losses in season-long weedy plots were 94% and 91% without PRE herbicide application and with PRE herbicide application, respectively, for SRP (see upper limit of the curves, Figure 2, Tables 5 and 6). Similarly, TRP without PRE herbicide and with PRE herbicide applications resulted in 95% and 93% corn yield loss, respectively (Figure 3, Tables 5 and 6). Such high yield losses in 2015 are likely a result of a lack of precipitation (Table 2).

Yield losses in 2016 were not high when compared to the other years, for both planting patterns and herbicide regimes (Figure 2). For example, corn yield losses in season-long weedy plots grown without PRE herbicide application were 50% and 47% in SRP and TRP, respectively, in comparison with the other two years. Corn yield losses in season-long weedy plots grown with PRE herbicide application were 41% and 37% in standard row planting and Twin-row planting patterns, respectively (upper limit of the curves, Figure 2).

In 2017, corn yield loss was greater than 2016, but lower than 2015 in plots with and without PRE herbicide treatments in both planting patterns. At SRP, in season-long weedy plots, yield loss was up to 80%, while in TRP, yield loss was 72% without PRE herbicide application. On the other hand, application of S-metolachlor plus terbutilazyne in season-long weedy plots resulted in 69% and 62% corn yield losses in SRP and TRP, respectively (Figure 2).

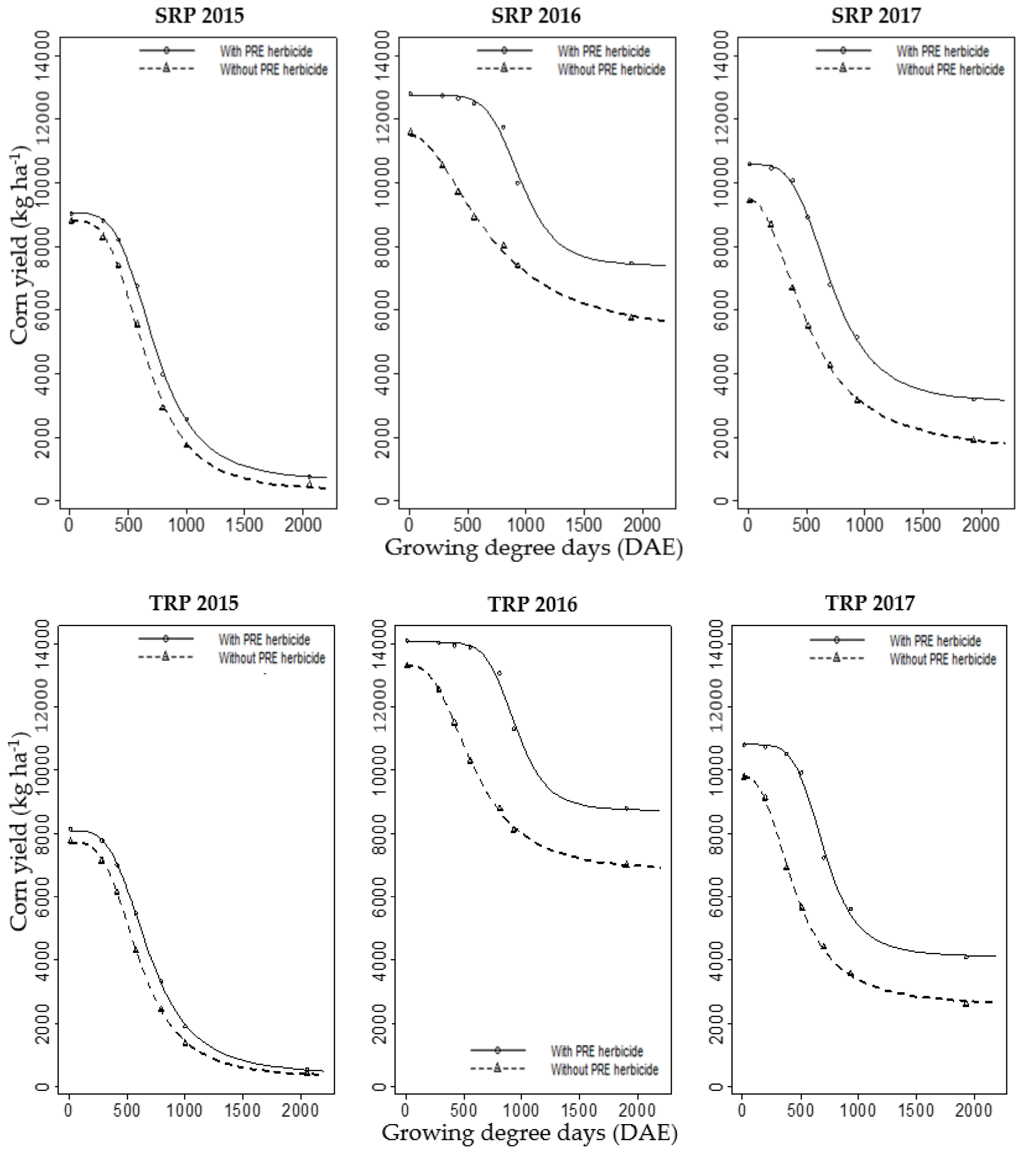

Figure 2. Crop yield (kg ha^{-1}) response to increasing duration of weed interference as represented by growing degree days (days after emergence, DAE) in corn grown without pre-emergence (PRE) herbicide and with PRE herbicide treatments in Padina in Serbia (2015–2017).

3.4. Critical Time for Weed Removal (CTWR)

The CTWR in corn was estimated utilizing a 5% acceptable yield loss threshold [21]. Overall, the CTWR significantly varied between the two herbicide regimes.

In all cases, the CTWR occurred earlier in plots without PRE herbicides, regardless of the planting pattern and years. For example, the CTWR in SRP ranged from 133 to 279 GDD without PRE herbicide treatment, which corresponded to 16 to 19 DAE or the V1–V2 leaf stages of corn (Table 6). Meanwhile, with PRE herbicide treatment, the CTWR in the same planting pattern occurred from 342 to 599 GDD, corresponding to 25 to 58 DAE or the V4–V10 leaf stages of corn (Table 6).

Similarly, in TRP without PRE herbicide treatment, the CTWR ranged from 147 to 255 GDD, corresponding to 18 to 22 DAE or V2–V3. The CTWR in TRP with PRE herbicide treatment started at 306 to 627 GDD, corresponding to 22 to 61 DAE or V3–V11 (Table 6).

Table 5. Corn yield loss (%) in response to increasing duration of weed interference represented by growing degree days (GDD after emergence) at two patterns of planting (SRP and TRP) with two levels of herbicide application in corn grown without PRE herbicide and with PRE herbicide during 2015, 2016, and 2017, in field experiments conducted in Padina, South Banat District, Serbia. Regression parameters represent a four-parameter log-logistic model.

Year	Planting Pattern	Herbicide Application	Regression Parameters (±SE)			
			B	C	D	I50
2015	SRP	With PRE	−3.9 (0.2)	−0.1 (0.8)	93.0 (1.2)	728.6 (10.1)
		Without PRE	−3.5 (0.2)	−0.2 (1.1)	96.8 (1.4)	647.5 (12.4)
	TRP	With PRE	−3.6 (0.1)	0.6 (0.7)	95.3 (0.9)	688.6 (6.8)
		Without PRE	−3.4 (0.1)	0.4 (0.7)	96.4 (0.9)	606.1 (6.5)
2016	SRP	With PRE	−6.3 (0.2)	−0.3 (1.0)	42.3 (2.0)	957.3 (27.9)
		Without PRE	−2.0 (0.1)	−0.7 (1.1)	56.3 (1.9)	701.1 (40.3)
	TRP	With PRE	−7.1 (0.6)	0.2 (0.8)	38.0 (1.5)	949.5 (20.4)
		Without PRE	−2.7 (0.1)	−0.04 (0.7)	49.4 (1.0)	592.9 (13.9)
2017	SRP	With PRE	−3.8 (0.3)	−0.1 (0.9)	71.1 (1.8)	711.4 (14.9)
		Without PRE	−2.2 (0.1)	−0.8 (0.8)	84.2 (1.4)	517.4 (11.9)
	TRP	With PRE	−5.0 (0.7)	−0.1 (1.4)	61.8 (2.4)	703.8 (22.2)
		Without PRE	−2.5 (0.1)	−0.7 (1.0)	74.2 (1.4)	473.9 (11.9)

Abbreviations: ST, standard planting pattern; TW, Twin-row planting pattern; B, the slope of the line at the inflection point; C, the lower limit; D, the upper limit; I50, the growing degree days giving a 50% response between the upper and lower limits (also known as inflection point).

Table 6. The CTWR (based on a 5% acceptable yield loss) influenced by planting pattern and two levels of herbicide application in corn grown without PRE herbicide and with PRE herbicide expressed in growing degree days (GDD), corresponding crop growth stage (CGS), and days after emergence (DAE).

Year	Planting Pattern	Herbicide Application	CTWR		
			GDD (±SE)	DAE	CGS
2015	SRP	With PRE	342.5 (4.8)	25	V4
		Without PRE	279.2 (5.4)	19	V2
	TRP	With PRE	306.1 (8.1)	22	V3
		Without PRE	255.8 (7.1)	18	V2
2016	SRP	With PRE	599.9 (17.5)	58	V10
		Without PRE	160.9 (9.2)	16	V1
	TRP	With PRE	627.1 (13.8)	61	V11
		Without PRE	202.6 (11.2)	20	V2
2017	SRP	With PRE	325.3 (16.7)	37	V5
		Without PRE	132.9 (7.7)	16	V1
	TRP	With PRE	392.8 (30.1)	41	V6
		Without PRE	147.6 (9.8)	19	V2

Abbreviations: SRP, standard planting pattern; TRP, Twin-row planting pattern; CGS, crop growth stage; CTWR, critical time weed removal; V1 to V11, number of leaves per plant; GDD, growing degree days; DAE, growing degree days.

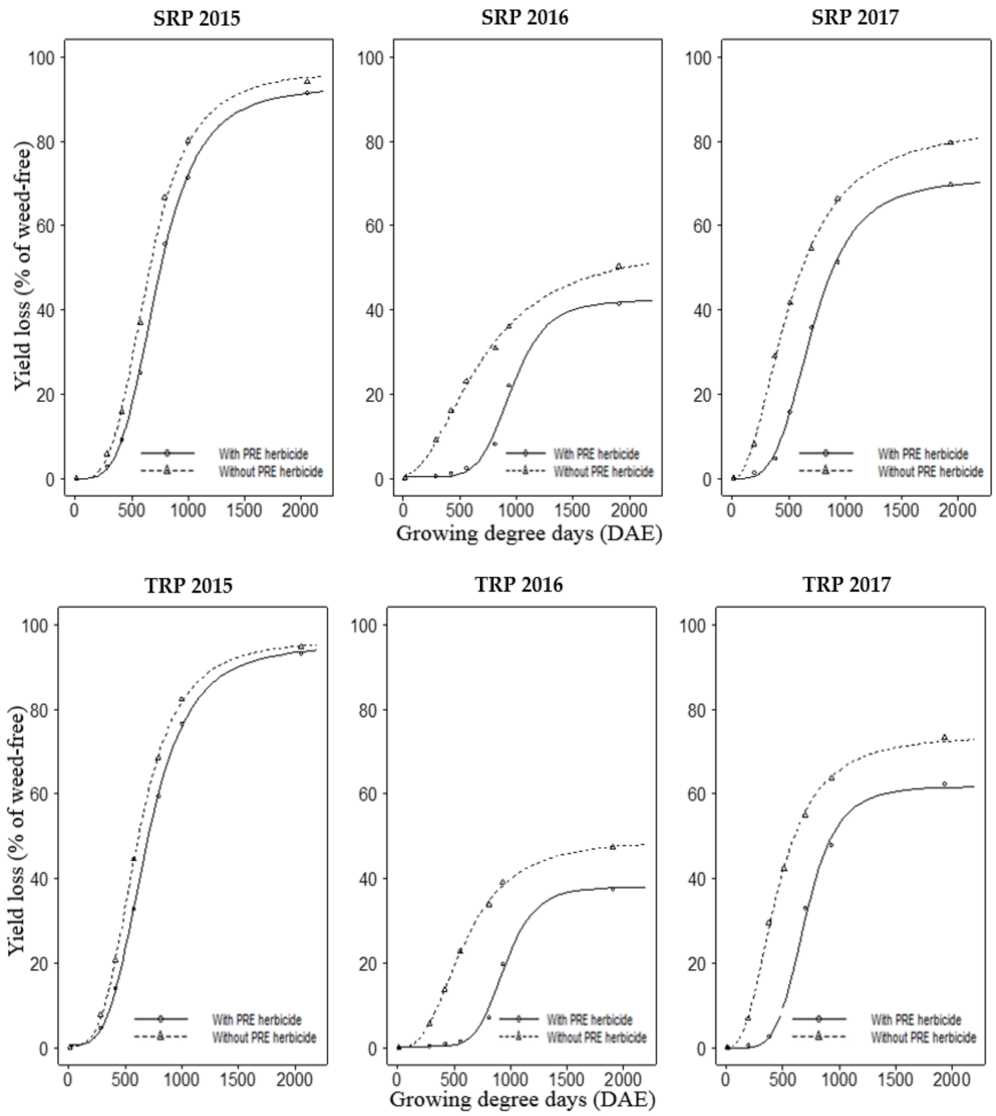

Figure 3. Corn yield loss (% of weed-free) response to increasing duration of weed interference as represented by growing degree days (DAE) grown without PRE herbicide and with PRE herbicide applications in standard row (SRP) and twin-row (TRP) planting patterns, at Padina, Serbia, 2015–2017.

4. Discussion

Twin-row planting is a newer system of growing corn in the world and in Serbia. Therefore, comparing TRP to SRP systems and determining the CTWR in both systems were the objectives of this study.

It appeared that TRP was slightly better for suppressing the weeds as compared to SRP based on weed density counts at the VT stage of corn in the weedy treatment. This might be due to early crop canopy closure resulting in shading weeds and having a lower weed density per area. Similarly, other researchers reported that corn planted at higher plant populations and narrower rows (e.g., TRP) could make better use of the habitat by expediting canopy closure and light interception, which gave the crop a competitive advantage over weeds [47–50],

In our study, the plots with PRE herbicides across years had a lower number of weeds compared to plots without PRE herbicides, due to the effectiveness of herbicides, which was confirmed in many studies [51–53].

Corn yield varied between years, where 2015 (dry year) was lower in both planting patterns than 2016 (very rainy year) or 2017 (average year) in all treatments. Under wet year conditions (e.g., 2016), yield was 10% higher in TRP than in SRP. In 2015 (dry year), TRP had a lower yield than SRP in all treatments, compared to wetter years of 2016 and 2017 (Table 2). These results are similar to those reported by Gözübenli [54], which reported that yield and sowing system are correlated with agroecological conditions and corn hybrids. In general, significant differences in yield that occurred could be a result of differences in the number of plants per unit area (SRP = 80,000 ha^{-1} plants and TRP = 93,900 ha^{-1} plants), the presence or absence of soil herbicides, and differences in meteorological conditions between seasons (Table 2).

Yield losses in both planting patterns were greater in plots without PRE herbicide treatment compared to the plots with PRE herbicide treatment. The level of yield loss also varied among planting patterns and between years likely due to different weather conditions (dry versus wet years) and types of weeds (grassy versus broadleaf) present across site–years. Other studies have shown that the growth and yield of corn were affected by the duration of weeds effectively with the weed density [55,56].

Proper timing of weed control is an important part of agriculture production. The CTWR differed between planting patterns, herbicide regimes, and years (Figure 3). Based on the 5% acceptable yield loss level, CTWR was similar in SRP (V1–V2) and TRP (V2 stage) without PRE herbicides. However, in the plots with PRE herbicide treatment, CTWR in SRP ranged from the 4–10-leaf stages, and a slightly wider range from 3 to 11 leaves in TRP plots was observed. These results clearly indicate that PRE herbicides are important for protecting corn yield regardless of the planting pattern.

5. Conclusions

Utilizing the concept of CTWR can help in making decisions on when to initiate post-emergence weed control, which saves time and expenses. Corn producers should not allow weeds to interfere in their fields for more than 132 to 279 GDD, equivalent to the V1 (16 days after emergence (DAE)) to V2 (19 DAE) corn growth stages. The use of PRE herbicides delayed CTWR to at least 25 DAE, and, in some cases, to 58 DAE, which is equivalent to 342 to 599 GDD (or V4 to V10 growth stages) in SRP, and up to 61 DAE (which is equivalent to the V11 growth stage or 627 GDD) in TRP. In years with sufficient precipitation (or in irrigated fields), the TRP system may provide a better yield potential due to the higher plant population (93,000 plant ha^{-1}), in comparison with the SRP system.

Finally, the results of this study also reaffirm the well-known benefit of PRE herbicides for controlling early-emerging weeds, which are the most competitive against the crop. Furthermore, PRE herbicides could also delay the need for post-application of foliar herbicides or the use non-chemical weed control. In fields where weed resistance exists, PRE herbicides containing multiple (or alternative) modes of action can aid in managing herbicide-resistant weeds.

Author Contributions: Conceptualization, S.K. and S.V.; methodology, D.B.; software, D.N.; validation, S.K.; formal analysis, D.N.; investigation, S.V.; resources, D.N.; data curation, D.B.; writing—original draft preparation, D.N.; writing—review and editing, S.K. and S.V.; visualization, D.N.; supervision, S.V.; funding acquisition, S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia, grant number: 451-03-9/2021-14/200116.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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