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Original paper

Manipulation of sunflower population density and herbicide rate for economical and sustainable weed management

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Abstract Field study tested weed control efficacy, crop yield and economic return using various weed management strategies in sunflower growing with different population density. Treatments included four rates of PRE emergence application of S-metolachlor + fluchloridon and one POST emergence application of flumioxazin + quizalofop-p-ethyl. PRE-em application (1.4 + 2.4 and 1.2 + 2.0) provided at the higher crop densities (70 000) best weed control. However, PRE- em treatments with lower doses (0.8 + 1.6 and 1.0 + 1.8) and POST- em application did not maintain acceptable control of dominant weeds. Grain yield increased with the crop density, but did not statistically differ between applied herbicide treatments. Finally, the implication of this study demonstrated that sole application of tested herbicide treatments at higher crop sowing density (60 000 and 70 000) was found to be economically the best alternative strategy for reducing weed infestation and achieving a better yield.

Keywords Sunflower, weed control, herbicides, crop density, economic evaluation.

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Introduction

Sunflower (*Helianthus annuus* L.) is sensitive to weed infestation. This crop is usually planted in 70 cm row spacing at low densities and develops slowly during the initial weeks (PINKE & al [1]). As reported by KNEZEVIC & al. [2], critical period of weed removal in sunflower without using a PRE emergence herbicide is ranged from 14 to 26 days after crop emergence (DAE) and corresponds to the V3 to V4 of sunflower development stages. Weeds that emerge and establish themselves during this (critical period) time can be very competitive and can reduce sunflower yield. This knowledge can also reduce the amount of herbicide needed if a single, well-timed application reduces the need for a second application (MARTIN & al [3]).

Herbicide options for sunflowers have expanded with the introduction of effective POST emergence herbicides and with the development of herbicide-resistant cultivars. However, compared to most other row crops, sunflower growers still have a very limited range of herbicides available to control broadleaved weeds (JURSIK & al [4]; MALIDŽA & al [5]).

Identification of appropriate herbicide and application rate is crucial step for the sunflower growers, because it must provide consistent and sustained efficacy and meet requirements over a wide range of conditions (DOYLE & STYPA, [6]). Herbicides, however, also face some challenges regarding safety and environmental issues, and the evolution of herbicide resistant weeds. To avoid or delay the development of herbicide resistant weeds, a diverse, integrated weed management (IWM) practice is required for reducing weed population size and minimizing crop losses. IWM, as a sustainable approach, combines all available weed control techniques, including preventative measures, monitoring, crop rotations, tillage, crop competition, mechanical and physical control, herbicide rotation, herbicide mixtures, biological control, nutrition, irrigation, flaming, etc. in a way that minimizes economic, health and environmental risks (SWANTON & al [7]).

Currently, cultural weed control methods increase in importance (MOHLER [8]). The main goal of this approach is to reduce the competition imposed by weeds through the enhancement of a crop competitive ability in order to improve the ability of the crop itself to suppress weeds. GODEL [9] recognized the value of higher seeding rates of cereal grains for reducing weed competition. Seeding rate, as he suggested, should depend on variety, size of kernels, condition of land, and degree of weed infestation. Many other researchers have also shown that higher plant populations and closer rows reduced evaporation, increased efficiency of water use, and gave higher yields by increasing the energy available to the crop (OLSEN & al [10]).

Particularly, larger crop plants like sunflower have an advantage of initial size in competition by suppressing the growth of their smaller neighbour weeds, and this phenomenon is known as "size-asymetric competiton" (WEINER [11]). Although weeds have faster growth rates than the crop (MOHLER [8]), immediatelly after germination sunflower seedlings are larger than a weed seedlings, which increase the degree of competitive size-asymetry in community. Moreover, the advantage of size in competition increases with the crop density (SCHWINNING & WEINER [12]) resultiung the better suppresion of weeds at higher than at lower crop density.

Since judicious manipulation of these factors can be a highly effective component of an IWM, the objective of this study is to evaluate the economic benefit and potential role of increased crop density in sunflower weed management.

Materials and Methods

Field experiments were conducted in North eastern part of the Republic of Croatia near the municipality Valpovo in Osijek-Baranja County on a meadow lessive soil type. This region experiences a warm and moderate to dry climate with the highest rainfall regime in spring. An average yearly temperature 11.4°C and average yearly rainfall of 699 mm is suitable for sunflower production. Sunflower hybrid NK Brio (Syngenta), mid late maturity group, was planted on April 18 and April 23 in 2016 and 2017 respectively, following the standard sunflower growing procedure for the region.

Table 1. Herbicide treatments and dose used in the study

Treatment	Dose l/ha	Time of application (DAS)*	
		2016	2017
T 1: S-metolachlor + fluchloridon	0,8 + 1,6	2	2
T 2: S-metolachlor + fluchloridon	1,0 + 1,8	2	2
T 3: S-metolachlor + fluchloridon	1,2 + 2,0	2	2
T 4: S-metolachlor + fluchloridon	1,4 + 2,4	2	2
T 5: flumioxazin + quizalofop-p-ethyl	1,5 + 1,5	18 + 25	20 + 26
T 6: control	-	-	-

***** DAS = days after sowing

The experimental design was split-plot with four replications. The main plot was the sunflower target population (50 000, 60 000 and 70 000 plants ha^{-1}), and the subplot was the different herbicide treatments (Table 1) where PRE-emergence application of S-metolachlor and fluchloridon in various application rate were compared with POST emergence flumioxazin and quizalofop-p-ethyl applied later during the critical period of weed removal

(KNEZEVIC & al [2]). Weedy control was also included for comparison. Plot size was 5 m × 15 m with six crop rows in each plot.

Residual weed community were assessed according to mean relative abundance value of each weed species calculated by plots as follows: (relative density + relative frequency)/2 as described by DERKSEN & al [13]. Weed density and species composition were recorded each year at the end of growing season after the effect of crop density and herbicides application have become evident. Weeds were counted from randomly placed sixteen (0.5 × 0.5 m) quadrats per each plot to overcame the problem of patchy nature of the weed community.

Crop harvest were conducted approximately two weeks after physiological maturity (heads yellow, with bracts turning brown). Samples for grain yield determination were obtained by hand harvesting third and fourth rows of each plot, dried and threshed with stationary thresher. Seeds were adjusted to 9% moisture.

Finally, an economic analysis was performed to determine economic benefits of weed management on different crop population density, based on gross profit analysis using partial budgeting. According the procedure explained by OSIPITAN & al [14], following calculations were made:

Harvested grain yield based on existing market prices were converted to total revenue (TR) and expressed in €/ha. The formula used to calculate the revenue is shown below:

$$TR = Y \times P$$

where TR was total revenue per hectare (€/ha), Y was total sunflower yield harvested in kilograms per hectare (kg/ha), P was market price for sunflower (€/kg).

Gross profit (GP) for each weed management strategy and sunflower population density was calculated by deducting the total revenue per hectare from the total variable cost. Formula used to calculate gross profit is:

$$GP = TR - TVC$$

where GP was the gross profit per hectare (€/ha), TR was total revenue per hectare (€/ha), and TVC was total variable cost of production (€/ha), calculated using the cost of seeds, fertilizers, pesticides and costs of agro-technic operations.

Cost-benefit ratio for each treatment was calculated by dividing gross profit by total variable cost of production using the following formula:

$$BC_{ratio} = GP / TVC$$

where BC_{ratio} was the cost-benefit ratio, GP and TVC were defined above.

Weed relative abundance, crop yield data and cost-benefit ratio were subjected to ANOVA by the PROC MIXED procedure in SAS (SAS v9.4, SAS Institute Inc., Cary, NC [15]) to test for the significance of years, sunflower target populations, treatment combination, replication and their interaction. All data were tested for homogeneity at $\alpha = 0.05$ (PETERSON [16]) and pooled when interaction did not occur. The means were separated with Fisher's Protected LSD test at $\alpha = 0.05$.

Results

Fifteen different weeds including two grasses and thirteen dicots were observed during the study period (Table 2). Weed relative abundance and species composition did not significantly vary with years. Dicot weeds (87%) were predominant than the grasses (13%).

Table 2. Floristic composition of weed community in sunflower during study period

Weed species	Life cycle*	Mean relative abundance	
		2016	2017
Ambrosia artemisiifolia L.	AD	0.64	0.69
Setaria viridis (L.) Beauv.	AG	0.36	0.31
Echinochloa crus-galli (L.) P. Beauv.	AG	0.26	0.16
Chenopodium album L.	AD	0.16	0.36
Matricaria chamomilla L.	AD	0.13	0.12
Plantago major L.	PD	0.11	0.13
Polygonum aviculare L.	AD	0.08	0.06
Polygonum lapathifolium L.	AD	0.07	0.13
Galinsoga parviflora Cav.	AD	0.07	0.06
Convolvulus arvensis L.	PD	0.03	0.05
Ranunculus repens L.	PD	0.03	-
Rorippa austriaca (Crantz) Besser	PD	0.30	-
Geranium molle L.	AD	0.03	-
Gypsophyla muralis L.	AD	0.03	-
Capsella bursa-pastoris (L.) Med.	AD	-	0.06

Life cycle: AD = annual dicot, AG = annual graminoid, PD = perennial dicot

Two annual broadleaved species (*Ambrosia artemisiifolia* and *Chenopodium album*) and two annual grasses (*Setaria viridis* and *Echinochloa crus-galli*) were the major weeds during the study with the highest mean relative abundance in both years.

Across the sunflower population densities and years, those weeds predominate in each herbicide treatments, and particularly in control, untreated plots. These primary dicot and grass species accounted for 75-88% of the density of the total weed population at each site. The rest of the weed community were with significantly lower mean relative abundance values.

With the exception of crop sowing rate ($P < 0.0001$), herbicide ($P = 0.0027$) and their interaction ($P = 0.0099$) no other main effect or interactions were observed for relative weed abundance (Table 3). Higher crop density resulted in lower weed relative abundance in all herbicide treatments, but not in control plots (Figure 1).

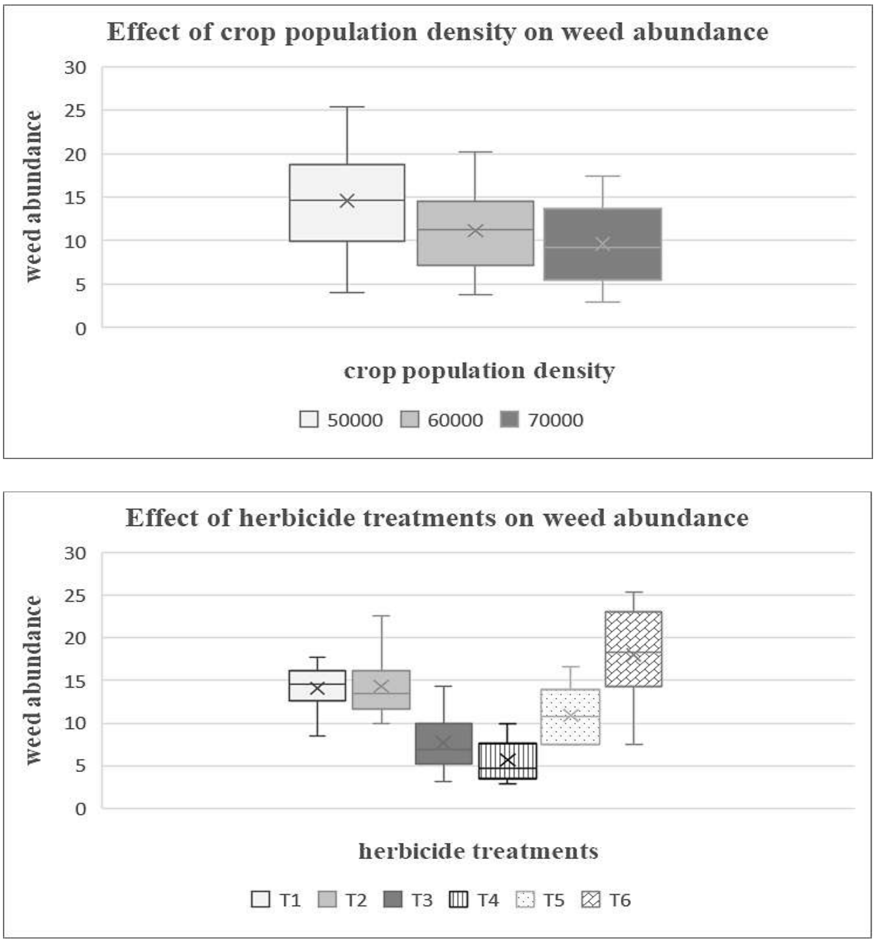

Figure 1. Effect of crop population density and herbicide treatments on relative weed abundance in sunflower (for treatment description see Table 1).

Herbicide application significantly decreased weed infestation compared to untreated control (Figure 1). PRE emergence application of herbicides with the rate 1.4 + 2.4 and 1.2 + 2.0 provided at the higher crop densities, the best weed control, by inhibiting the germinating weed seedling early in the growing season and giving the crop a competitive advantage. However, PRE emergence treatments with lower dose (0.8 + 1.6) did not maintain acceptable control of dominant weeds as well as POST emergence application of flumioxazin + quizalofop-p-ethyl.

Grain yield generally increased with the crop density ($P < 0.0001$). Significant differences ($P = 0.0105$) were also noticed between study years (Table 3, Figure 2). Herbicide treated plots have significantly higher yield compared to control. However, when control, weed infested plot is excluded from the analysis, no significant difference between herbicide treatments appears.

Table 3. Effect of crop density and herbicide dose on weed abundance, sunflower yield and cost-benefit ratio during the study period (2016-2017)

Treatments and interactions	df	Weed abundance		Sunflower yield		Cost-benefit ratio	
		F-value	P > 0	F-value	P > 0	F-value	P > 0
Year	1	4.87	0.0732	10.6	0.0105	4.67	0.0352
Crop density	2	22.27	< .0001	98.22	< .0001	21.17	< .0001
Herbicide	5	50.64	0.0027	1.97	0.1687	2.61	0.0214
Y * CP	2	1.76	0.1311	0.32	0.8506	1.99	0.8531
Y * H	5	0.75	0.5274	0.04	0.9996	1.4	0.3216
CP * H	10	6.95	0.0099	0.05	0.9959	1.05	0.0348
Y * CP * H	10	1.58	0.2064	0.62	0.4469	0.82	0.9962

Treatments: Y = year; CD = crop density; H = herbicide

All management practices resulted in significantly better monetary returns when compared to weedy check (Table 4). Regarding to Cost-benefit ratio (Table 3, Figure 3) there was significant year effect (P = 0.0352) because in second year the yield increase, as well as the commodity price and the cost of herbicides. Crop density (P < 0.0001), herbicide application (P = 0.0214) and their interaction (P = 0.0348) were also significant.

Finally, the implication of this study demonstrated that sole application of tested herbicide treatments at higher crop sowing density (60 000 and 70 000) was found to be economically the best alternative strategy for reducing weed infestation and achieving a better yield.

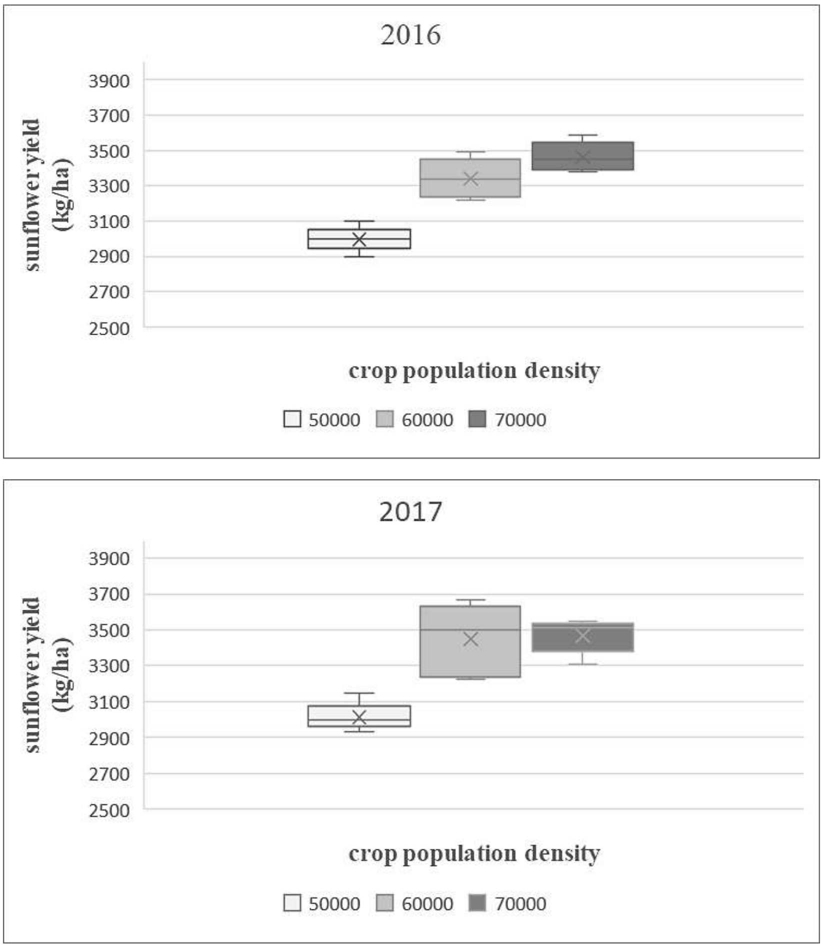

Figure 2. Sunflower yield (kg/ha) at different crop density during the study period.

Discussion

Sunflowers are planted in a wide row spacing and usually with lower planting density than many other row crops which makes it more vulnerable to weed competition (BRUNIARD & MILLER [17]; ELEZOVIĆ & al [18]). By providing a little canopy during the beginning of the growing season this crop can be seriously infected with a mixed population of summer weeds that competes for moisture, nutrients and light. Control of these weeds is difficult and sunflower producers have fewer herbicide options, particularly for broadleaf weed control compared to most other row crops (MALIDŽA & al [5]).

Weed community that developed during this experiment were typical weed flora of the row crops in the region (RADOJČIĆ & al [19]). This result is with concordance to SMATANA & al [20], who claims that in canopy of sunflower most frequently occurred weeds are *Chenopodium* spp., *Polygonum* spp., *Echinochloa crus-galli*. Also, PINKE & al [1] reported that *Ambrosia artemisiifolia* represents a great challenge for sunflower growers in Hungary, as well as it is a problem in North-Croatian sunflower fields (ŠTEFANIĆ & al [21]).

Table 4. Economic evaluation of weed management strategies for sunflower crop growing under different population density

Herbicide treatment*	2016				2017			
	TVC	Yield	TR	GP	TVC	Yield	TR	GP
50 000 plants								
T1	627.0	2900	1150.9	523.9	637.5	3010	1226.8	592.4
T2	640.3	3000	1181.1	540.7	652.1	2990	1220.5	568.4
T3	656.5	3100	1211.2	554.7	656.4	3150	1271.1	605.6
T4	674.9	2990	1178.0	503.1	688.9	3000	1223.7	534.8
T5	634.9	3000	1181.1	546.2	645.6	3000	1223.7	578.1
control	542.2	1310	671.4	129.2	542.2	1205	656.8	114.7
60 000 plants								
T1	635.8	3220	1247.4	611.6	643.3	3250	1302.6	659.3
T2	649.1	3250	1256.4	607.3	660.9	3225	1294.7	633.8
T3	665.3	3410	1304.7	639.4	674.3	3600	1413.2	738.9
T4	683.8	3490	1328.8	645.1	697.7	3670	1435.3	737.6
T5	643.7	3340	1283.6	639.9	654.4	3500	1381.6	727.1
control	551.0	1520	747.9	196.9	551.0	1300	686.8	135.9
70 000 plants								
T1	643.7	3500	1302.8	659.1	651.2	3310	1321.6	670.4
T2	657.0	3380	1295.7	638.6	668.8	3450	1365.8	697.0
T3	673.2	3450	1316.8	643.6	682.2	3520	1387.9	705.7
T4	691.7	3590	1359.0	667.3	705.6	3510	1384.7	679.2
T5	651.6	3400	1301.7	650.1	662.3	3550	1397.4	735.0
control	558.9	1735	799.6	240.7	558.9	1322	696.9	138.1

*for treatment description see Table 1
TVC = total variable costs (€/ha); TR = total revenue (€/ha); GP = gross profit (€/ha)

Higher crop densities and higher application rate of PRE emergence herbicide S-metolachlor + fluchloridon (1,4 + 2,4 and 1,2 + 2,0) gave commercially acceptable weed control and satisfactory suppressed the growth of troublesome dicot weed species until the canopy closure. Weeds that germinate after that period were unable to compete with the crop, and those who survived, remain small and caused no significant reduction in crop yield. POST-emergence application of flumioxazin + quazalofop-p-ethyl (1,5 + 1,5) was less acceptable even applied inside of the three week of crop growth (critical period of weed control, KNEZEVIC & al [2]), but no significant yield reduction was observed compared to the best options.

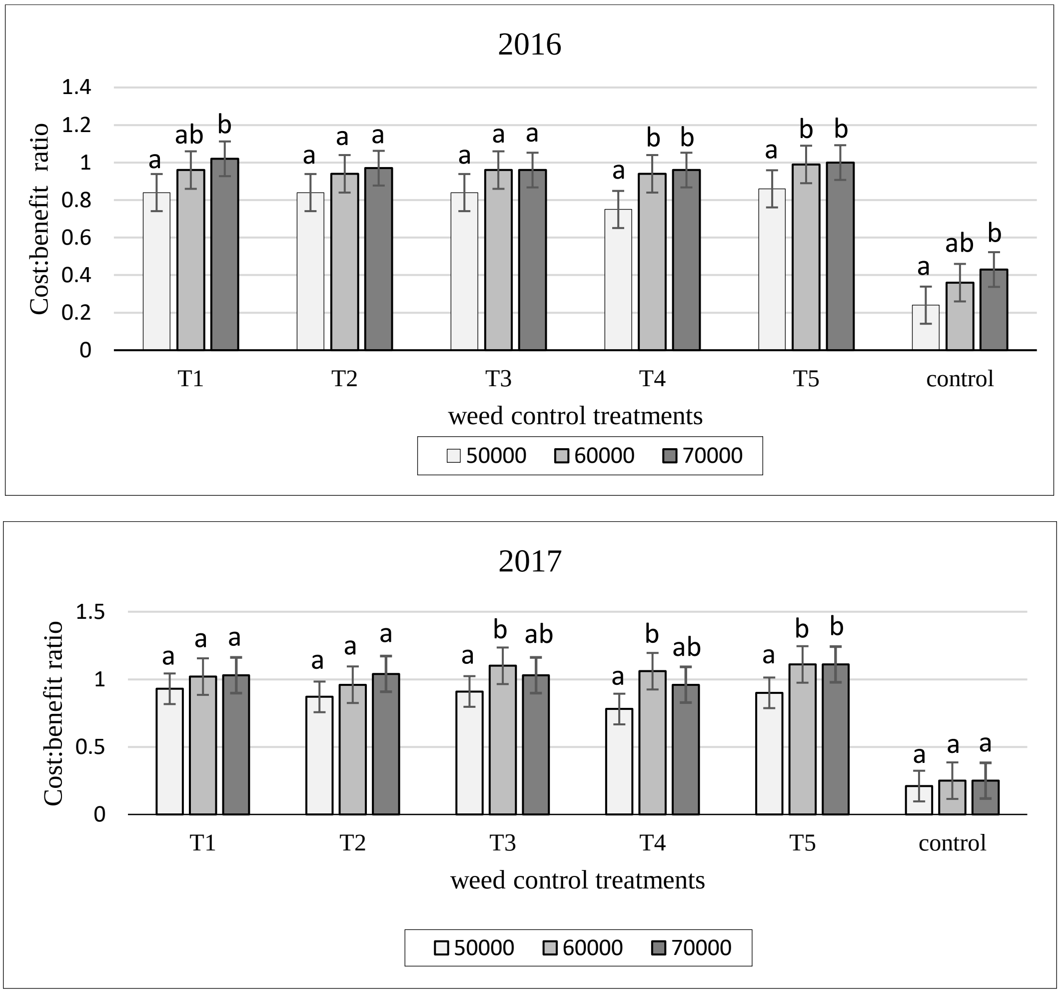

Figure 3. Cost-benefit ratio of weed management methods at different crop density during the study period (for treatment description see Table 1) Means with different letters represent significant differences within treatments according to the Fisher's Protected LSD test at $\alpha = 0.05$.

Herbicides are dominant weed control method worldwide (SELVAKUMAR & al [22]). However, there is a increased awareness by farmers to choose effective weed management strategies that minimize environmental impacts and decrease the possibility for development resistant weed populations while remaining profitable (SWINTON & van DEZNYE, [23]). Among the management practices that are likely to affect weed suppression is manipulation with crop density. Higher plant population in this experiment (60 000 and 70 000 per hectare) enable sunflower to compete more effectively with weeds by expediting canopy closure and light interception. Therefore, coupling herbicide application with cultural practices such as planting density could lead to more effective weed management in sunflower. Effective weed suppressions with increasing crop density were also reported in similar studies (MOHLER [8]; KRISTENSEN & al [24]), and occurred, as WEINER & al [25] emphasizes, when crop-weed competition is size asymmetric. This means that early size advantage of the crop is theoretical base for prediction of positive effect of increased crop density on weed suppression. But when weeds are taller than crop early in the growing season, size-asymmetric competition will be to the advantage of the weeds. Practically, this study indicates that one herbicide application in sunflower by complementing the higher crop density could help to optimize yield and increase profitability and cost-benefit ratio.

Conclusions

Weed community in sunflower growing with different population density consists of fifteen different weed species. Major weeds having the highest mean relative abundance throughout the study were annual broadleaved species (*Ambrosia artemisiifolia* and *Chenopodium album)* and annual grasses (*Setaria viridis* and *Echinochloa cruss-gali*).

Higher crop density reduced weed relative abundance in all herbicide treatments. PRE emergence application of S-metolachlor and fluchloridon with the rate 1.4 + 2.4 and 1.2 + 2.0 provided at the higher crop densities (70 000) best weed control. However, the same herbicide combination but with with lower doses (0.8 + 1.6 and

1.0 + 1.8) and POST emergence application of flumioxazin + quizalofop-p-ethyl did not maintain acceptable control of dominant weeds.

Grain yield increased with the crop density, but did not statistically differ between applied herbicide treatments.

Sole application of tested herbicide treatments at higher crop sowing density (60 000 and 70 000) was found to be economically best alternative strategy for reducing weed infestation and achieving better yield.

Conflict of Interest

The authors has no conflict of interest to declare.

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