AGRICULTURAL AND FOOD SCIENCE

Agricultural and Food Science (2025) 34: 79–90

https://doi.org/10.23986/afsci.159817

Timing and intensity of weed harrowing in spring barley

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At present weed harrowing is gaining significance in conventional agriculture as there is a growing trend to reduce the application of pesticides. Unfortunately, the harrowing is partially damaging to crop plants. The objective of the study was to find the optimum timing and intensity (1–3 harrow passes) of weed harrowing in spring barley. A 3-year one-factor field experiment was conducted on the alluvial loamy sand soil. Weed harrowing was conducted at different growth stages of barley. The additional treatments were: the increased seeding rate of barley by 20%; herbicide application and untreated control. At least two passes with spring-tine harrow: at barley emergence and next at tillering or at the 2-leaf stage and tillering were needed for the significant weed density reduction but only the first treatment did not reduce barley grain yield. Three harrow passes: at barley emergence, the 2-leaf stage and tillering most efficiently reduced weed density but were also most damaging to barley. The experiment showed that when planning weed harrowing twice during barley growth the cereal needs a long period of time to recover after the first cultivation.

Key words: mechanical weed control, spring-tine harrow, seeding rate, herbicide application, weed density, barley density

Introduction

There is a growing need for replacing the chemical method of weed control with more environmentally friendly alternatives that can be used by farmers. A spring-tine harrow, which is probably the most popular harrow for weed control could be used in most crops. Some models are more than 20 m wide, and the implement can be pulled by a tractor with high speed allowing a quick weed control on large areas (Kouwenhoven 1997). According to Coleman et al. (2019) controlling weeds with a harrow is several orders of magnitude less energy consuming than, for example, flame weeding or hot air application to weeds. Harrowing is a popular method of weed control on organic farms in Northern Europe, being the one of a few agricultural practices which effectively reduces weed density in spring cereals (Hofmeijer et al. 2021). The tine weeder is also the first choice implement for controlling weeds in small grains that has been used by organic farmers managing areas larger than one thousand hectares in the Northwest United States (Tautges et al. 2016). Weed harrowing is also considered among some other weed control methods in a scenario for Australian farmers in which herbicides are not permitted (Beckie et al. 2021).

Nevertheless, harrowing is detrimental to crop plants, thus the decision on the timing and intensity of weeding is difficult for a farmer. One has to find the highest selectivity of the harrowing which is the ratio between weed density reduction and crop damage measured immediately after harrowing (Rasmussen 1991). This implies that during tine weeding the weeds should be at growth stages when they are easily uprooted or covered by soil thrown by the harrow while the opposite is true for the crop.

Because the resistance to the damaging effect of harrowing increases with the size of the crop plants (Dastgheib 2004, Sobkowicz et al. 2020, Zeng et al. 2021), growth stages such as tillering or stem elongation have been frequently chosen in the weed harrowing experiments for cereals. In most of the research, however, no increase in grain yield after the weeding was observed (Bàrberi et al. 2000, Dastgheib 2004, García-Martín et al. 2007, Pardo et al. 2008, Pannacci et al. 2017, Gerhards et al. 2021). It may have resulted from the advanced growth stage of some difficult to eradicate weeds which later competed intensely with a crop (Pannacci et al. 2017, Pannacci et al. 2018).

The research demonstrates that a spring-tine harrow controls weeds more effectively when they are in the cotyledon stage of growth (Lundkvist 2009, Pannacci et al. 2017, Gerhards et al. 2021, Zeng et al. 2021), while Kurstjens et al. (2000) claim that the best weeding efficiency could be reached when harrowing is performed at the white-thread stage of weeds, i.e., when they germinate and grow underground. Moreover, the complete covering of weed seedlings is a prerequisite for a successful weed control (Baerveldt and Ascard 1999, Mohler et al. 2016, Merfield

Received 13 March 2025 / Accepted 13 June 2025

The Scientific Agricultural Society of Finland

et al. 2020). The early stages of weeds coincide with the early stages of cereals which are then vulnerable to the damage caused by harrow (Rydberg 1993, Dastgheib 2003, Dastgheib 2004, Zeng et al. 2021).

Although most of the research, which assessed the efficiency of weed harrowing, considered only the weeds which survived the disturbance, several studies have shown that the new flush of weeds appears after each harrow pass. It could probably happen because the germination of weed seeds had been stimulated by tine weeding (Dastgheib 2004, Cirujeda and Taberner 2006, Lundkvist 2009, Johnson and Holm 2010, Zeng et al. 2021, Lacroix et al. 2025). Alba et al. (2020) observed even higher weed density after weed harrowing in lentil than in untreated control plots. Zeng et al. (2021) showed a higher efficiency of weed harrowing at the 2-leaf stage of wheat than at tillering when the weed density was measured immediately after each cultivation event. But after a period of time, the opposite was true due to a new flush of weed seedlings that appeared after earlier weed control. Some authors believe that the late emerging weeds cannot compete intensely with a crop when the crop is in an advanced stage of growth (Johnson and Holm 2010, Adeux et al. 2019, Lacroix et al. 2025). On the contrary, Cirujeda and Taberner (2006) suggest that those new flushes of weed seedlings, which appear after early harrowing, require the additional control. Lundkvist (2009) observed early and late emerging types of weeds in his experiment. Both were effectively controlled in their cotyledon stages by two harrowings separated in time.

The decision on the timing of weed control in cereals results also from an observed pattern of weed growth which is typical for a given region. For example, pre-emergence weed harrowing is popular in Scandinavian countries where weeds germinate earlier than crops (Cirujeda and Taberner 2006, Brandsæter et al. 2012).

In some experiments, the efficiency of weed harrowing has been compared with the efficiency of herbicides. No negative effect of correctly chosen and applied herbicide on crop plants is taken into consideration, and weed control efficacy may reach 100% when all the weeds are killed (Pannacci and Tei 2014, Saile et al. 2023). The advantage of chemical weeding over weed harrowing does not always translates into an increase in crop yield, in particular when weed density is low and their competition with the crop is not intense (Garcia-Martin et al. 2007, Pardo et al. 2008, Lacroix at al. 2025). The appropriate solution is then using weed harrowing first and, if necessary, supplementing the method with a chemical weeding which is in line with the idea of integrated weed management (Lacroix et al. 2025).

Another method of weed control without herbicides is to increase seeding density of a crop. The increased plant density of an unweeded crop builds up the pressure of a plant stand on weeds and sustains crop yield which is then similar to that of weeded crop (Weiner et al. 2010).

The objective of the study was to find the optimum method of weed harrowing in spring barley. We hypothesized that (I) at the low density of weeds, only a single harrowing would be necessary for an efficient weed control and the weeding should be performed between germination and cotyledonous growth stages of early weeds. We observed that the stages usually coincide with the 2-leaf-stage spring cereals sown in late March. We also assumed seasonally varying weed infestation, when more passes with the harrow are necessary to control dense stand of weeds. Thus, we hypothesized that (II) harrowing at the barley emergence and then at its tillering should be most efficient. The assumption behind this hypothesis is that harrowing at the barley emergence delays the emergence of early weeds. As the result, they are small at the tillering stage of barley and easy to control together with late emerging weeds. Moreover, the previous study showed that cereals are resistant to the destruction caused by spring-tine harrow at the plant emergence and tillering (Sobkowicz et al. 2020).

Material and methods

Location of field experiment and agronomic practices

The experiment was conducted at the Swojec Agricultural Experiment Station in Wrocław, Poland (51^{o}07’ N 17^{o}08’ E) belonging to Wrocław University of Environmental and Life Sciences, on alluvial loamy sand soil in 2018, 2019 and 2020. Some chemical properties of the soil are presented in Table 1. Crops grown before establishing the experiment were: winter rye in 2018 and winter triticale in 2019 and 2020. Conventional plow-based soil tillage was used on the whole experimental area. Each year during the seedbed preparation in spring, the experimental field was fertilized. Nitrogen (ammonium nitrate) was applied at a rate of 40 kg N ha^{-1}. The potassium fertilizer rates (potassium chloride) were: 80 kg K_2O ha^{-1} in 2018, and 2019, and 110 kg K_2O ha^{-1} in 2020. In 2018 and 2019 no phosphorus fertilization was used, while in 2020 due to low availability of P for plants in the soil, the element was applied at a rate of 70 kg of P_2O_5 ha^{-1} (superphosphate). At barley tillering an additional 40 kg N ha^{-1} (ammonium nitrate) was applied.

Table 1. Some chemical properties of soil taken from 0–20 cm soil layer of the experiment area

Year	N_{total}	$P_{available}$	$K_{available}$	$C_{organic}$	pH	
	g kg^{-1} of soil				H_2O	KCl
2018	0.52	0.085	0.100	7.1	7.1	6.5
2019	0.38	0.162	0.125	9.4	7.0	6.1
2020	0.75	0.037	0.085	n.a.[1)]	n.a.	6.5

n.a. = not analyzed

Field design and experimental treatments

Each year a field experiment was established according to the randomized complete block design with a method of weed control as an experimental factor. The experimental plots were 3 m wide and 10 m long. Two-row spring barley (*Hordeum vulgare* L.) cv. Paustian was seeded along the plots at a row spacing of 12.5 cm to a depth of 3–4 cm. The sowing dates were: 04.04.2018, 21.03.2019 and 20.03.2020. There were seven weed control treatments replicated four times in the experiment: four mechanical control treatments, a herbicide application, increased seeding rate of barley and untreated control. Spring-tine harrow 'Aktywator' (producer: EXPOM® sp. z o.o. Krośniewice, Poland) was used for a mechanical weed control. The harrow had five 3 m long steel beams arranged one after another and positioned perpendicular to the direction of tractor travel. Each beam had 24 steel tines. The arrangement of tines on the beams gave a 2.5 cm spacing of the working tines. The tines were 7 mm in diameter, 40 cm long and had bent ends that penetrated the soil surface to a maximum depth of 3–4 cm. During the experiment, the tines were set on the harrow at an angle of 29^{o} backwards in relation to the ground and the bent ends penetrated the soil at right angle. In the experiment the harrowing was conducted: a) at plant emergence and tillering of barley (ET); b) at emergence, the 2-leaf stage and tillering (ELT), c) at the 2-leaf stage (L), and d) at the 2-leaf stage and tillering (LT). Dates of harrowing and a time period between the dates is presented in Table 2. A single tractor pass with the harrow along plant rows of a plot was performed at a given growth stage of barley, with a speed of 10 km·h^{-1}. In the chemical weed control treatment (HC) Mustang 306 SE herbicide (florasuram 6.25 g l^{-1} + 2,4-D 300 g l^{-1}, producer: Dow AgroSciences® Poland sp. z o.o.) was used at a rate of 0.6 l ha^{-1}. The herbicide controls dicotyledonous weeds. It was applied on 10.05.2018, 13.05.2019 and 13.05.2020, when barely was at the tillering stage. On plots with the increased seeding rate of barley (S+) the density of seeding was elevated by 20% compared the standard rate of 320 viable seeds of barley per 1 m^2. Untreated control plots (UC) were left without any weed control.

Table 2. Dates of weed harrowing in the experiment

Growth stage of barley	2018		2019		2020	
	date	time period between stages (days)	date	time period between stages (days)	date	time period between stages (days)
Emergence	17 Apr		5 Apr		9 Apr	
		6		11		11
2-leaf stage	23 Apr		16 Apr		20 Apr	
		14		9		14
Tillering	7 May		25 Apr		4 May	

Assessments

The covering of barley plants by soil thrown by harrow passes was determined immediately after harrowing. At emergence and at the 2-leaf stage of barley, plants which were visible above the soil surface were counted in an area of 0.5 m^2 in four replicates per plot. The counts were also done in the untreated control plots in four replicates per plot at emergence and two replicates per plot at the 2-leaf stage of barley. In order to measure the burial of barley plants in the soil after harrowing, the crop soil cover (CSC) (Rasmussen et al. 2008) was calculated according to the formula: $CSC = 100 \times (1 - pn_h / pn_0)$, where pn_h is the number of plants per 1 m^2 that were not covered by the soil after harrowing, while pn_0 is the number of plants per 1 m^2 in the control plots. At tillering of barley when distinguishing of individual plants was impossible, two pictures were taken in harrowed and control plots using a digital camera. Each picture covered 0.75 m^2 (1 m × 0.75 m) of the soil surface. The area was determined by placing a rectangular frame on the ground and taking a 4 × 3 picture. The pictures were then displayed on the computer screen in the Power Point® program and covered with an uniformly distributed net of 200 dots. The dots laying above green parts of the plants in the picture were counted and the CSC was calculated as 100 × ($1 - gd_h / gd_0$), where gd_h is the number of dots that covered the green plant parts in the picture from the harrowed plot and gd_0 is the number of dots covering green plant parts in the picture from the control plot. It is important to note that among treatments with harrowing the plant counts at plant emergence were only done in plots of ET treatment because it was assumed that the harrowing had the same effect on the plants of ELT treatment. Similarly, at the 2-leaf stage of barley, plant counts were carried out only in the plots of L and ELT treatments, but not in the plots of LT treatment where barley was harrowed for the first time, like the barley in plots of L treatment.

At the full maturity of barley, cereal plants were manually uprooted from an area of 0.5 m^2 of each plot and counted. The ears of the entire sample were counted and threshed in the sample thresher. Thousand grain weight was determined on the basis of 500 grains per plot. At the full maturity of barley, the grain was harvested from the plots using the combine plot harvester on 25.07.2018, 25.07.2019 and 10.08.2020. The grain was weighed and the yields were adjusted to 15% moisture content.

At heading and the harvest of barley, the weeds were counted in the area of 0.5 m^2 in two replicates per plot. The counts included the weeds which survived a weed control as well as the newly germinated ones. At the barley harvest, the weeds from both sampling areas were cut aboveground, dried in a glasshouse and weighed.

Statistics

The data for each year were analyzed separately by using Statistica® ver. 13.3 computer program (StatSoft Poland Sp. z o.o. 2017). ANOVA for the experiments conducted according to the randomized complete block design was applied to all data. Transformations log10(x+1) were applied to the weed data in order to stabilize the variance while the crop soil cover data were arcsin square root transformed. The means were compared using the post hoc Tukey HSD test with the significance level $\alpha = 0.05$. The Pearson correlation coefficient was calculated to measure the linear relationship between the barley plant density and grain yield and also between the weed density and the grain yield of barley.

Weather

The weather conditions differed in the experimental years (Table 3). The growing season in 2018 was generally dry, with monthly precipitations lower than those averaged over the 50-year period. Low air temperatures in March 2018 resulted in a delay of the barley sowing time. However, this did not have a consequence for the timing of harrowing due to the high temperatures in April and May 2018 which accelerated the development of barley plants. A very low level of precipitation was noted in April 2020 with only 9.6 mm of rain. Barley plants suffered from a water deficit in the soil being small and thin. Thus, they were sensitive to soil covering and the damage done by the harrowing performed at the 2-leaf stage. June 2020 was unusually wet, but no consequence of high precipitation during that month was observed in the experiment.

Table 3. Weather data recorded in Agro- and Hydrometeorology Observatory in Agricultural Experiment Station Swojec in Wrocław during the experimental years together with the long-term averages

Month	Monthly mean air temperatures (°C)				Total monthly rainfall sums (mm)			
	2018	2019	2020	average1968–2017	2018	2019	2020	average1968–2017
March	1.2	6.5	5.1	3.6	26.5	23.9	23.4	33.0
April	13.9	9.9	9.3	8.7	24.6	40.7	9.6	37.2
May	17.1	12.3	11.9	14.0	49.4	92.8	74.6	57.1
June	19.5	22.5	17.8	17.1	51.1	23.3	191.5	73.6
July	20.8	19.9	19.0	18.9	72.9	48.1	19.4	87.0
August	21.7	20.5	20.2	18.4	11.4	85.4	95.1	70.1
Sum					235.9	314.2	413.6	358.0

Results

In 2018 emerging barley plants were very sensitive to the soil covering, which later resulted in their reduced resistance to harrowing at the 2-leaf stage (Table 4). Therefore, significantly more plants were buried in the soil after tine weeding at the 2-leaf stage when harrowing was preceded by earlier harrowing (ELT) than in a case when harrowing was applied for the first time (L and LT). No difference in the crop soil cover (CSC) after harrowing was observed at the tillering stage of barley in 2018. The CSC did not differ significantly in 2019. The low precipitation level in April 2020 slowed the barley growth and at the 2-leaf stage barley plants were thin and vulnerable to soil covering. Furthermore, the plants were also unable to fully recover from burial, and after the third pass of the spring-tine harrow (ELT) the CSC was significantly higher than after the two harrowings provided that the harrowings omitted the 2-leaf stage of barley (ET).

Table 4. Crop soil cover (CSC) after harrowing of barley

Treatment symbol[1)]	2018			2019			2020		
	Timing of harrowing								
	E	L	T	E	L	T	E	L	T
	%								
ET	71a[2,3)]		37b	51a		53a	78abc		21d
ELT		46ab	37b		46a	64a		92a	73bc
L		12c			41a			82ab	
LT			25bc			64a			57c

[1)] Letters E, L and T denote timing of weed harrowing during barley growth stages: E – emergence, L – 2-leaf stage, T – tillering. At a given growth stage one pass with spring-tine harrow per plot was performed. Connected capital letters indicate that harrowing was conducted in a treatment at those growth stages of barley; [2)] Percentage data were arcsin ($\sqrt{(x/100)}$) transformed before ANOVA, backtransformed data are presented in the table; [3)] Means within a given year sharing a common letter are not significantly different at 5% probability level

Dicotyledonous weeds dominated the weed community in the experiment. They comprised 87%, 81% and 83% of the total number of weeds in 2018, 2019 and 2020, respectively, in the untreated plots at the heading of barley (the data not shown). Common lambsquarters (*Chenopodium album* L.) and field pansy (*Viola arvensis* MURR.) dominated weed flora in 2018. In 2019 common lambsquarters was a dominant weed, while in 2020 weed community was diverse with three most abundant species: common lambsquarters, small geranium (*Geranium pusillum* L.) and barnyardgrass (*Echinochloa crus-galli* L.).

Two passes with the harrow per plot were needed for significant 77% weed density reduction and three for 87% reduction while measured at the heading of barley in 2018 (Table 5). Also, at the barley harvest 74% and 77% significantly less weeds were observed in plots of LT and ELT treatments, respectively, compared to UC. A single pass with the harrow at the 2-leaf stage of barley was insufficient for weed density reduction in 2018. Only the most intense weed harrowing (ELT) significantly decreased the weed biomass (by 84%) recorded at the barley harvest compared to the weed biomass in UC treatment. In 2018, the increased seeding rate of barley or herbicide application had no effect on weed density and biomass compared to UC.

With the exception of L treatment, the harrowing significantly reduced the plant density of barley in 2018 (Table 5). The harvest data show that compared to UC, barley population was 28–31% lower after two passes with the harrow while the barley harrowed three times had 39% lower plant density than the untreated control. Those initially thinned stands produced more tillers per plant, giving similar densities to UC ear. A significant difference was observed only between densely sown barley (S+) and barley harrowed three times. There was also a tendency to increase thousand grain weight due to harrowing, but only barley weeded at the 2-leaf stage and then at tillering had a significantly 21% higher thousand grain weight than barley in UC treatment. Barley harrowed three times (ELT) or at the 2-leaf stage and tillering (LT) yielded 31% and 22% less grain, respectively, than the untreated control. In 2018 other treatments with weed harrowing (L and ET), increased barley seeding rate and herbicide application did not have an effect on grain yield when compared to UC. Nevertheless, barley sown in a dense stand (S+) yielded significantly more grain than harrowed barley.

Table 5. The effect of weed control method on weeds and barley in 2018

Treatment symbol[1)]	Weed density		Aerially-dry weed biomass	Yield components of barley			
	heading of barley	harvest	harvest	plant density	ear density	TGW[2)]	grain yield
	(plants m^{-2})		(g m^{-2})	(plants m^{-2})	(ears m^{-2})	(g)	(t ha^{-1})
UC	(22) 1.36 a[3,4)]	(39) 1.61 ab	(25) 1.42 a	268 ab[2)]	503 ab	36.5 b	4.30 ab
S+	(19) 1.29 a	(55) 1.75 a	(18) 1.29 ab	326 a	579 ab	36.6 b	4.75 a
HC	(20) 1.31 a	(22) 1.35 abc	(8) 0.96 ab	301 a	628 a	39.2 ab	4.21 ab
ET	(5) 0.78 bc	(17) 1.25 bc	(6) 0.82 ab	193 c	470 ab	41.3 ab	3.56 bc
ELT	(3) 0.58 c	(9) 1.02 c	(4) 0.72 b	164 c	384 b	41.6 ab	2.97 c
L	(11) 1.07 ab	(19) 1.31 abc	(8) 0.96 ab	202 bc	439 ab	39.2 ab	3.51 bc
LT	(5) 0.77 bc	(10) 1.05 c	(6) 0.87 ab	184 c	425 ab	44.0 a	3.34 c

1) UC – untreated control, S+ – seeding rate of barley increased 20%, HC – herbicide application, letters E, L and T denote timing of weed harrowing during barley growth stages: E – emergence, L – 2-leaf stage, T – tillering. At a given growth stage one pass with spring-tine harrow per plot was performed. Connected capital letters denoting barley growth stages indicate that harrowing was conducted in a treatment at those growth stages; 2) TGW – thousand grain weight; 3) Before ANOVA analysis weed data were log10(x+1) transformed and means are presented in the table with backtransformed means in parentheses; 4) Means within column sharing a common letter are not significantly different at 5% probability level

In 2019 no effect of harrowing or increasing barley seeding rate on the density and the biomass of weeds was observed in the experiment (Table 6). The only efficient weed control method was a herbicide application. At heading and at the harvest of barley, HC plots had significantly 72% and 77% lower weed density than UC plots, respectively, and 95% lower weed biomass at the barley harvest.

Table 6. The effect of weed control method on weeds and barley in 2019

Treatment symbol[1)]	Weed density		Aerially-dry weed biomass	Yield components of barley			
	heading of barley	harvest	harvest	plant density	ear density	TGW[2)]	grain yield
	(plants m^{-2})		(g m^{-2})	(plants m^{-2})	(ears m^{-2})	(g)	(t ha^{-1})
UC	(46) 1.67 a	(71) 1.85 a	(43) 1.65 a	251 abc	632 ab	41.4 b	4.50 ab
S+	(49) 1.70 a	(75) 1.88 a	(38) 1.59 a	276 a	609 abc	42.4 ab	4.73 ab
HC	(13) 1.15 b	(16) 1.23 b	(2) 0.45 b	270 ab	635 a	41.9 ab	5.20 a
ET	(44) 1.66 a	(66) 1.83 a	(16) 1.23 a	212 abc	531 abc	44.2 ab	4.19 b
ELT	(47) 1.68 a	(102) 2.01 a	(15) 1.21 a	189 c	537 abc	41.6 ab	3.80 b
L	(23) 1.39 ab	(59) 1.77 a	(17) 1.25 a	185 c	486 c	45.5 a	4.71 ab
LT	(30) 1.49 ab	(74) 1.87 a	(43) 1.65 a	194 bc	498 bc	45.1 ab	3.85 b

[1)] UC – untreated control, S+ – seeding rate of barley increased 20%, HC – herbicide application, letters E, L and T denote timing of weed harrowing during barley growth stages: E – emergence, L – 2-leaf stage, T – tillering. At a given growth stage one pass with spring-tine harrow per plot was performed. Connected capital letters denoting barley growth stages indicate that harrowing was conducted in a treatment at those growth stages; [2)] TGW – thousand grain weight; [3)] Before ANOVA analysis weed data were log10(x+1) transformed and means are presented in the table with backtransformed means in parentheses; [4)] Means within column sharing a common letter are not significantly different at 5% probability level

Compared to UC treatment, in 2019 tine weeding had no significant effect on the plant density at the harvest and on the barley grain yield (Table 6). The barley harrowed only once during the growing season (L) had a significantly lower ear density by 23%, but 10% higher thousand grain weight than barley under control treatment. In 2019, the herbicide-treated barley yielded significantly more grain than the harrowed barley, with the exception of L treatment. The increased seeding rate had no effect on the barley yield.

No changes in the weed density were noted at barley heading in 2020, while at the harvest HC, ET and ELT treatments had significantly lower weed density than UC by 49%, 44% and 47% respectively (Table 7). Compared to the untreated control, herbicide application provided the greatest reduction (77%) in weed biomass recorded at the barley harvest and the only effective way of harrowing significantly decreasing weed biomass (by 63%) was ET.

Table 7. The effect of weed control method on weeds and barley in 2020

Treatment symbol[1)]	Weed density		Aerially-dry weed biomass	Yield components of barley			
	heading of barley	harvest	harvest	plant density	ear density	TGW[2)]	grain yield
	(plants m^{-2})		(g m^{-2})	(plants m^{-2})	(ears m^{-2})	(g)	(t ha^{-1})
UC	(80) 1.91 a	(106) 2.03 a	(35) 1.56 a	252 ab	902 a	46.0 a	4.49 a
S+	(70) 1.85 a	(90) 1.96 ab	(21) 1.35 a	268 a	907 a	45.0 a	4.23 a
HC	(75) 1.88 a	(54) 1.74 b	(8) 0.93 c	277 a	896 a	45.9 a	4.44 a
ET	(51) 1.71 a	(59) 1.77 b	(13) 1.16 bc	189 bc	857 a	50.4 a	3.99 ab
ELT	(67) 1.84 a	(56) 1.76 b	(23) 1.38 ab	185 bc	750 a	48.5 a	2.76 d
L	(76) 1.89 a	(83) 1.92 ab	(17) 1.26 abc	163 c	659 a	48.3 a	3.51 bc
LT	(55) 1.75 a	(67) 1.83 ab	(18) 1.28 abc	189 bc	778 a	47.3 a	3.28 cd

[1)] UC – untreated control, S+ – seeding rate of barley increased 20%, HC – herbicide application, letters E, L and T denote timing of weed harrowing during barley growth stages: E – emergence, L – 2-leaf stage, T – tillering. At a given growth stage one pass with spring-tine harrow per plot was performed. Connected capital letters denoting barley growth stages indicate that harrowing was conducted in a treatment at those growth stages; [2)] TGW – thousand grain weight; [3)] Before ANOVA analysis weed data were log10(x+1) transformed and means are presented in the table with backtransformed means in parentheses; [4)] Means within column sharing a common letter are not significantly different at 5% probability level

There was a clear tendency for the barley population to be reduced due to harrowing in 2020, but only the L treatment had significantly 35% lower plant density than the UC at the harvest of barley (Table 7). The ear density and the thousand grain weight of barley were not affected by the methods of weed control. A severe 39% decrease in barley grain yield was observed after three passes of the harrow, (ELT) while L and LT treatments decreased yield by 22% and 27%, respectively, compared to UC. The S+, HC, and ET yields did not differ significantly from the UC yield in 2020.

In 2018 and 2020, the barley grain yield was significantly correlated with the density of the cereal at the harvest, increasing with an increasing plant density (Fig. 1).

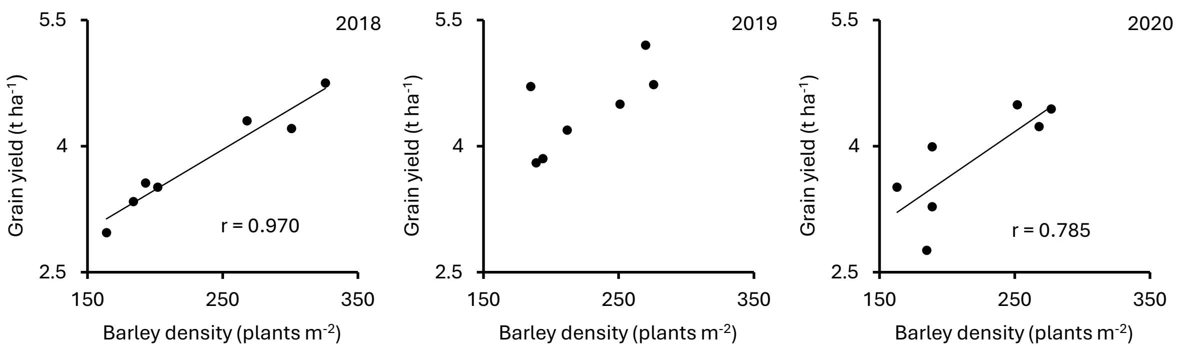

Fig. 1. Linear relationship between barley plant density at harvest and grain yield in 2018–2020. Each dot is a treatment mean (n=7). Correlation coefficients (r) and regression lines are shown for statistically significant correlations (*p*= 0.05).

In the first year of the experiment, a positive correlation was observed between weed density at the barley heading and harvest and grain yield, while in 2019 a negative correlation was observed between the two variables at harvest of the cereal (Fig. 2). There was no linear relationship between weed density and yield of barley in 2020.

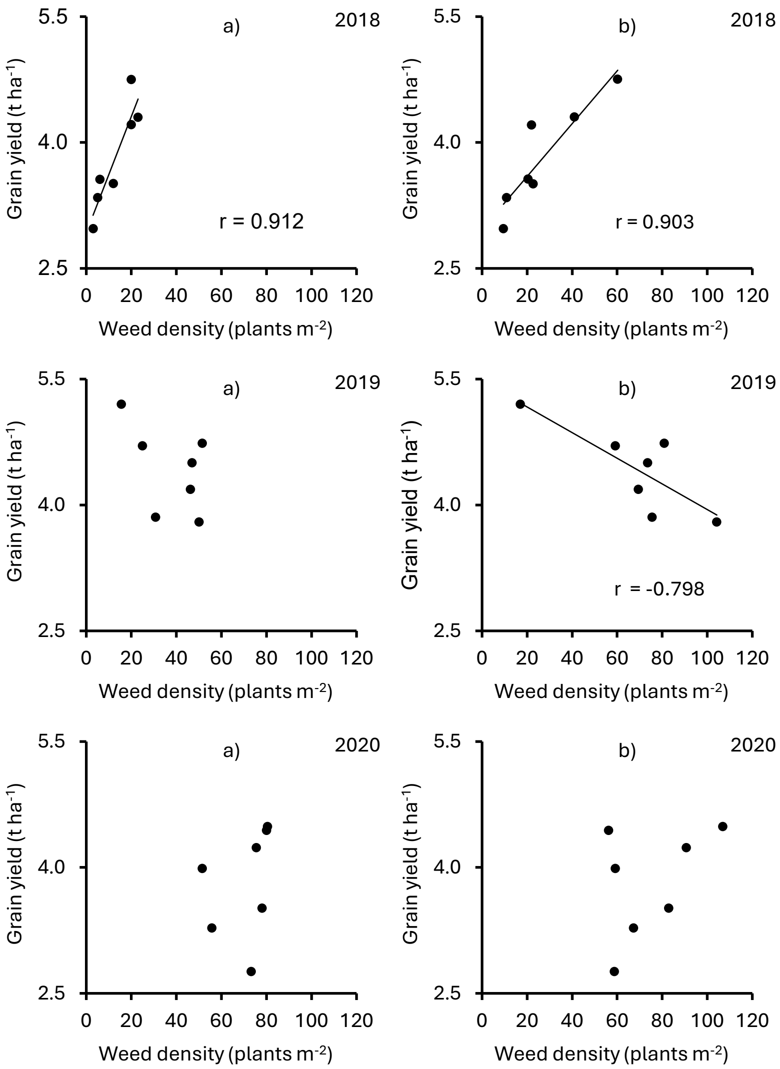

Fig. 2. Linear relationship between: a) weed density at heading, b) weed density at harvest and grain yield of barley in 2018–2020. Each dot is a treatment mean (n=7). Correlation coefficients (r) and regression lines are shown for statistically significant correlations (*p*= 0.05).

Discussion

The experiment shows that weed harrowing had a detrimental effect on the barley, reducing its plant density. The positive correlation between the barley density and the grain yield in two out of three years of the study suggests that the plant density reduction was the main cause of the grain yield decline. Little data are available on the reduction in plant density of cereals caused by harrowing. Dastgheib (2003) and Dastgheib (2004) noted only insignificant reductions in the plant density of wheat after the post-emergence tine weeding but the changes had no effect on the grain yield. Also, Bàrberi et al. (2000) did not find any effect of the depth of post-emergence weed harrowing on the plant number of durum wheat. Our previous study (Sobkowicz et al. 2020) showed however, that the single tine weeding of the oat-triticale mixture at the 2-leaf stage decreased the plant density of both components.

In the present study barley compensated for the plant loss mainly by increasing head density and thousand grain weight, but the compensation was not full and the grain yields differed between some treatments with harrowing and untreated control. This is in disagreement with data of Wilson et al. (1993) where the compensatory response of thousand grain weight of harrowed winter wheat was sufficient to reduce differences in grain yield. Moreover, in the research of Sobkowicz et al. (2020), oat and triticale grown in the mixture compensated successfully for the plant loss caused by harrowing mainly, by increasing the number of grains per inflorescence. Rasmussen and Rasmussen (2000) showed that the compensatory mechanism may be weakened when there is a competition pressure from the weeds on a crop. It seems that it was not the case in our research. The lack of an increase in the grain yield of herbicide-treated barley compared to the untreated control shows that the competitive ability of barley was high and weed control was unnecessary. This is also confirmed by a mostly positive or insignificant correlation between the weed density and barley yield. This high competitive ability of two-row spring barley was shown in the experiments by Gerard et al. (2022) in which barley expressed a smaller yield decrease due to a weed competition than most Canadian cultivars of spring wheat. Hence, only the negative effect, if any, of weed harrowing on barley could have been detected in our study. The lack of yield gain after weed harrowing in cereals, resulted from the insignificant competitive weed pressure on a crop was earlier observed by Rasmussen et al. (2010), Naruhn et al. (2021) and Lacroix et al. (2025). The negative effect of weed harrowing on the yield of cereals compared to unweeded reference treatments was noted by other authors (Bàrberi et al. 2000, Lundkvist 2009, Sjursen et al. 2012). Sjursen et al. (2012) assumed that the grain yield decrease was caused by the destructive effect of the harrowing direction which was perpendicular to the rows with cereal plants at the 3–4-leaf stage of growth.

Our experiment shows that only once – at the 2-leaf stage of barley – when most of the weed plants were invisible being at the white-thread stage of growth, the efficiency of harrowing was lower than the efficiency of both methods employing two passes with the harrow. There were no differences in the weed density and biomass between the L and UC treatments in any year of the study. This contradicts our first hypothesis. The disadvantage of a single harrowing at the 2-leaf stage of barley occurred in 2020 and was manifested by the decrease in the grain yield. But the cause of that disadvantage was the long drought period in April. It made barley plants prone to the damaging effect of harrowing that resulted in CSC 82% which should be treated rather as an exception than as a norm. There is no data on the cereal yields at that CSC value in the literature. Gerhards at al. (2021) and Spaeth et al. (2020) noticed a trend towards reductions in cereal grain yield at the CSC 60–70%. Both authors underlined that these high CSC values are detrimental to cereal plants.

The research shows that dry soil conditions like those in our study in April 2020 should facilitate the efficacy of a mechanical weed control (Brown and Gallandt 2018). When the soil is dry, weeds are not able to recover easily after the mechanical disturbance, in particular, when they are uprooted (Cirujeda and Taberner 2006, Garcia-Martin et al. 2007). The mentioned relationship was not observed in our experiment and the weed density at the heading of barley did not differ among treatments.

The present study shows that among weed harrowing treatments tine weeding at plant emergence and next at tillering of barley (ET) was the only method that did not decrease grain yield in any year when compared to the untreated control. The advantage of ET treatment was particularly well visible in 2020, when due to the drought, barley plants at the 2-leaf stage were thin and prone to the destructive effect of harrow. Therefore, omitting the 2-leaf stage of barley by extending a break in the physical disturbance of the cereal caused by two harrowings was a better solution in 2020 than using harrow twice. The first time, at the 2-leaf stage and the second time, at tillering of barley (LT). The advantage of ET treatment is only partially consistent with our second hypothesis. A period of time that passed after harrowing at plant emergence was long enough for barley to recover from the disturbance before the second disturbance occurred, the harrowing at tillering. On the other hand, the predicted high efficiency of the method in controlling weeds was not observed.

The effect of tine harrowing on the weeds was strong in 2018 when three passes with the harrow (ELT) reduced the weed density measured at the barley heading by 86% and also decreased weed biomass at barley harvest by 84%. Unfortunately, this high efficiency of weed harrowing was achieved at the cost of cereal performance, causing a 31% decrease in the grain yield in 2018 and 39% in 2020. This shows that the selectivity of harrowing was exceptionally low for the treatment, which is in agreement with the observation of Rasmussen et al. (2008) and Gerhards et al. (2021) who found that the selectivity of weed harrowing in cereals decreases at greater intensities of the treatment. Lundkvist (2009) also observed that the best weed control treatment, comprising two passes with a spring-tine harrow separated in time, reduced the grain yield of spring oat and spring wheat. The author suggests that the high efficiency of the weed control without any gain in a crop yield or even with a reduction in crop performance is important in the long term, because it prevents the weed seed rain and thus weed infestation of the following crop. However, we consider that the yield decreases observed in our study for ELT treatment were too high to be accepted by farmers. Probably the time breaks between consecutive passes of harrow in the treatment were too short to allow barley to recover from the disturbances caused by harrow. The second reason was the fixed and aggressive setting of spring-tine harrow used in our study, the same in all treatments and years. Rasmussen et al. (2010) suggest adjusting the aggressiveness of a cultivation to the growth stage of a crop. According to a model presented by Rasmussen (2024), at low weed pressure and low selectivity the high intensity of harrowing may cause a grain yield decrease. An appropriate solution to avoid too aggressive operation of a spring-tine harrow could be that used by Lacroix at al. (2025). Each time, before planned harrowing, they adjusted a harrow after observing its effect on the weeds and wheat during trials performed outside the experimental area.

Increasing the barley seeding rate by 20% did not have any effect on the density and biomass of weeds nor on the grain yield of barley in the present experiment. In most research elevated seeding rates of cereals reduced weed density (Li et al. 2018) and biomass (Olsen et al. 2012, Li et al. 2018, Walsh 2019, Rasmussen and Rasmussen 2000, Rotchés-Ribalta et al. 2020, McCollough and Melander 2022, Xi et al. 2022), but the ranges of investigated densities in those studies were much wider than in our experiment. Probably, in the present study, the increase in the density of barley plants resulting from an elevated seeding rate was too small to exert the noticeable pressure on the weeds. On the other hand, using much higher seeding rate of a cereal than the standard one may cause plant lodging and the grain yield decrease (Johnson and Stevenson 2001). Moreover, the extra seed needed for sowing is also an additional production cost that may be difficult to accept by farmers, in particular, if it does not lead to a yield gain (Kolb and Gallandt 2012).

Conclusions

In conclusion, our research demonstrates that weed harrowing with a fixed and relatively aggressive setting of spring-tine harrow may reduce barley plant density, and consequently decrease the grain yield. The observed negative effect of the harrowing on barley was not counterbalanced by the expected yield gain from a successful weed control because the weed competition with barley was negligible. The inability of barley to compensate for plant loss is surprising, as small grain cereals are known for such a response to the plant density reduction. The experiment showed that harrowing is particularly destructive for 2-leaf-stage barley when the cultivation is conducted after a long period of the dry weather. Then the plants become frail and prone to soil covering being also unable to quick recovery. Harrowing 3 times during a period of less than one month is detrimental to barley and leads to a severe grain yield reduction. We conclude that in order to alleviate the destructive effect of harrowing on the barley the first harrowing pass should be performed at barley emergence and the second at tillering. The relatively high resistance of barley to the damage in those stages, together with a long period of time for plant recovery after the first pass, prevent barley from yield decrease. The future research should focus more on barley cultivars that are better able to recover from the disturbance caused by harrowing. In the research, the decision on how to set the harrow should be made directly before a harrowing operation.

Acknowledgements

We wish to thank Adam Machocki for skilled technical field assistance.

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