AGRICULTURAL AND FOOD SCIENCE

Agricultural and Food Science (2022) 31: 12–23

https://doi.org/10.23986/afsci.113476

The effect of timing and intensity of weed harrowing in triticale-lupin mixture on weeds and crops

Piotr Sobkowicz and Ewa Tendziagolska

Institute of Agroecology and Plant Production, Wrocław University of Environmental and Life Sciences, pl. Grunwaldzki 24a, 50-363 Wrocław, Poland

e-mail: piotr.sobkowicz@upwr.edu.pl

The aim of the study was to find the most beneficial time of weed harrowing with its intensity represented by the number of passes with spring-tine harrow executed on one day in a mixture of triticale (×*Triticosecale* Wittm.) and narrow-leaved lupin (*Lupinus angustifolius* L.). The randomized complete block design was applied in field conditions in 2015–2017. It comprised one factor, the timing and the intensity of post-emergence weed harrowing with the spring-tine harrow. The plots were harrowed once, twice, or three times on one day at six consecutive growth stages of triticale: BBCH 10, 11, 12, 13, 21, 22. Harrowing did not increase the grain yield of the triticale-lupin mixture, and when repeated three times at BBCH 21, it decreased the grain yield. The cereal was more resistant than lupin to timing and intensity of harrowing. The weeds were best controlled by a single cultivation conducted at the first leaf of triticale. This method caused a significant reduction in the density and the biomass of weeds at the anthesis of triticale and a reduction in the weed biomass at the full maturity of the mixture. Increasing intensity of harrowing by repeating cultivations had relatively weak influence on the weeds.

Key words: cereal-legume mixture, weed infestation, grain yield, resistance to burial index

Introduction

Multispecies cropping systems are known to provide crucial ecological services to farmers and have been widespread in developing countries where those services cannot be replaced by external inputs (Malézieux et al. 2009). In developed countries popular multispecies assemblages are represented by cereal-legume mixtures that are grown mainly in organic farms where they serve as a source of biologically fixed nitrogen to the agroecosystem (Bedoussac et al. 2015).

Weeds are suppressed with cereal-legume mixtures in a better way when compared to pure stands of grain legumes (Hauggaard-Nielsen et al. 2006, Corre-Hellou et al. 2011, Arlauskiene et al. 2014, Ranaldo et al. 2020). The reason for that is the usage of aboveground and belowground resources which are more complementary than pure stands, leaving only a small fraction of those resources for weeds (Haymes and Lee 1999, Hauggaard-Nielsen et al. 2001, Poggio 2005, Bedoussac et al. 2015). However, the weed suppression ability of cereal-legume mixtures does not exceed that of sole cropped small grain cereals (Corre-Hellou et al. 2011, Arlauskiene et al. 2014) and, like cereals, they also need weed control (Bedoussac et al. 2015).

The expansion of organic farming and its popularity among societies, including general trend to reduce chemical input in conventional agriculture, have encouraged scientists to examine non-chemical methods of weed control, such as harrowing (Brandsæter et al. 2012). Recent research has shown that weed harrowing is widespread in organic farms in Europe (Hofmeijer et al. 2021). While some experiments demonstrate that herbicides provide a better weed control than harrowing (García-Martín et al. 2007, Pardo et al. 2008), the others underline that harrowing maintains weed diversity more effectively (Armengot et al. 2013, Hofmeijer et al. 2021). According to Coleman et al. (2019), the total energy requirements for weed harrowing are much lower than those for herbicide use or for a thermal method or mulching. Moreover, the advantage of harrowing over similarly popular interrow hoeing is that the first method does not require wide row spacing of crops and is recommended for small grain cereals (Mertens and Jansen 2002, Pannacci et al. 2017b). In those crops, hoeing without compromising grain yield is limited because the cereals suppress weeds more effectively when grown in narrow rows than in wide rows (Drews et al. 2009, Lötjönen and Mikkola 2000, Pannacci et al. 2017b).

When cereal-legume mixtures are grown in a conventional agricultural system, in which the use of herbicides is accepted, chemical weeding is impossible because their components belong to different botanical families and that poses a problem with choosing appropriate herbicide. Thus, it seems that the real option to control weeds in cereal-legume mixtures is mechanical weeding. To date, all the experiments have been conducted to optimize-mechanical weed control in sole cropped cereals and legumes, but it may be assumed that the components of

Received 11 January 2022 / Accepted 12 April 2022
The Scientific Agricultural Society of Finland

the cereal-legume mixture differ in their response to mechanical weeding. According to Melander et al. (2005) monocotyledonous crops are more prone to harrowing than dicotyledonous ones. Lundkvist (2009) indicated that the one-time preemergence harrowing was sufficient to control weeds in pea without the decrease in yield of the species, while cereals needed two harrowings but they reduced their yields.

Assuming that in order to successfully control weeds in the pure stands of small grain cereals or grain legumes the single herbicide spraying is sufficient, the question arises whether one pass with a harrow will control weeds effectively. In the research by Armengot et al. (2013), single harrowing was sufficient to reduce the density and biomass of weeds which resulted in the increased yield of organic cereals. Brandsæter et al. (2012) showed that in spring cereals, single post-emergence harrowing was as effective as one pre-emergence and one post-emergence treatment. The research also shows that when the increased number of harrowings was needed to reduce weed density in cereals, it had minimal or even negative effect on cereal yield (Rydberg 1993, Wilson et al. 1993, Bàrberi et al. 2000, Steinman 2002, Cirujeda et al. 2003, Pardo et al. 2008, Lundkvist 2009, Rasmussen et al. 2010, Sjursen et al. 2012).

The results of experiments on the effect of weed harrowing on grain legumes vary. In experiments of Jensen et al. (2004) harrowing on more than one growth stage did not improve weed control in lupin but was detrimental to the crop, heavily reducing plant population. Rasmussen (1993) found an additive negative effect of repeated harrowing on the yield of pea. In contrast, Lundkvist (2009) showed that pea was more resistant to harrowing than spring oats and wheat. In the research by Pannacci and Tei (2014), harrowing did not reduce plant density and the grain yield of soybean.

Being the whole-surface method, weed harrowing is known for its low selectivity (i.e., weed control/crop damage relationship). Thus, a decision on timing and intensity of the cultivation is problematic considering that when used inappropriately, harrowing may be detrimental to the young stand of a crop. Some studies show that at more advanced growth stages, cereals and weeds are more resistant to the destructive effect of harrow (Dastgheib 2004, Rasmussen et al. 2010, Rueda-Ayala et al. 2011, Pannacci et al. 2017b, Gerhards et al. 2021). It suggests that in order to control weeds effectively, more than a single cultivation is needed. In many experiments, harrowing was employed as a one of a few methods of weed control, but the number of harrowing treatments in those studies was probably too small to reveal maximum efficacy of the method. This presumption has frequently been formulated by the authors of the studies (Boerboom and Young 1995, Lötjönen and Mikkola 2000, Alba et al. 2020, McCollough et al. 2020).

The fact that herbicides cannot be used in cereal-legume mixtures and the lack of data on mechanical weed control were the factors which initiated our research. It was assumed that triticale and lupin would respond differently to harrowing, increasing the degree of unpredictability regarding the choice of the appropriate timing and intensity of the cultivation. Thus, the objective of the study was to find optimal time and intensity of weed harrowing for weed control and grain yield represented by the number of passes with spring-tine harrow conducted on one day in a triticale-lupin mixture. We hypothesized that single harrowing of the mixture when triticale has an unfolded third leaf, i.e. the stage when the first weeds are already present but small, would control weeds efficiently without significant injury to the crop.

Material and methods

Experimental site and cultural practices

The experiment was conducted over a three-year period in 2015–2017 at Wrocław University of Environmental and Life Sciences' Experimental Station in Swojczyce in Poland (51^{o}07' N 17^{o}08' E). It was established on alluvial loamy sand soil (Table 1). Preceding crops grown in the entire experimental area were: winter triticale (2014, 2015) and winter rye (2016). The experimental field received conventional plough-based tillage between the harvest of the preceding crops and the seeding of the triticale-lupin mixture. The appropriate proportions of the seeds of triticale (× *Triticosecale* Wittm.) cv. Andrus and narrow-leaved lupin (*Lupinus angustifolius* L.) cv. Kadryl were mixed before seeding. Both cultivars were listed in the "Common catalogue of varieties of agricultural plant species" in 2014 (EC 2014). The proportions were: 25% (120 grains m^{-2}) and 75% (80 seeds m^{-2}) of the recommended pure stand densities of triticale and lupin, respectively. This relative advantage given to lupin at seeding was due to its expected lower competitiveness in mixture with triticale. Sowings were done on: 30 March 2015, 31 March

2016 and 28 March 2017 to a depth of 3–4 cm. The row spacing was 12.5 cm. After sowing the mixture on the whole experimental area, the plots (3 m × 10 m) were arranged with a longer side perpendicular to the direction of the rows with plants. No fertilizers or pesticides were applied because it was assumed that the experimental conditions should resemble the situation during the conversion from conventional field management to organic. The plants were harvested by the combine plot harvester at full maturity of the mixture on: 11 August 2015, 12 August 2016 and 18 August 2017.

Table 1. Chemical properties of 0–20 cm soil layer of the experimental site in 2015–2017

Year	pH		$C_{organic}$	N_{total}	$P_{available}$	$K_{available}$
	H_2O	KCl	g kg^{-1} of soil			
2015	6.6	5.7	7.0	0.45	0.090	0.115
2016	6.8	6.3	7.5	0.57	0.104	0.083
2017	7.8	7.4	7.3	0.56	0.200	0.170

Design

Each year, the experiment was conducted according to the randomized complete block design with four replicates. It comprised one factor, the timing and intensity of post-emergence weed harrowing. The plots were harrowed once, twice, or three times on one day at six consecutive growth stages of triticale and the cultivation was not repeated later (Table 2). Single harrowing was performed at plant emergence (EM1) and when triticale had the first (FL1) and the second (SL1) unfolded leaf. At the three-leaf stage of triticale, the mixture was harrowed once (TL1) or twice (TL2), while at the beginning of tillering, once (BT1), twice (BT2), or three times (BT3), and at the full tillering, once (FT1), twice (FT2), or three times (FT3). The intensity of cultivation is represented here by the number of passes with a harrow per plot on one day. The control plots (CP) were those without weed harrowing.

Table 2. Timing of weed harrowing in 2015–2017

Year	Growth stage of triticale					
	BBCH 10[1] plant emergence (EM1)[2]	BBCH 11 1st leaf unfolded (FL1)	BBCH 12 2nd leaf unfolded (SL1)	BBCH 13 3rd leaf unfolded (TL1, TL2)	BBCH 21 beginning of tillering (BT1, BT2, BT3)	BBCH 22 full tillering (FT1, FT2, FT3)
2015	16 Apr	23 Apr	27 Apr	30 Apr	7 May	14 May
2016	13 Apr	19 Apr	25 Apr	6 May	10 May	17 May
2017	10 Apr	14 Apr	21 Apr	5 May	9 May	16 May

[1] BBCH scale (Bleiholder et al. 2005); [2] Capital letters denote growth stage of triticale while numbers denote the number of passes with a harrow per plot; EM=plant emergence, FL=first leaf unfolded, SL=second leaf unfolded, TL=third leaf unfolded; BT=beginning of tillering; FT=full tillering

Harrowing was performed perpendicularly to the direction of rows with plants with a speed of 10 km h^{-1} using 3-m wide spring-tine harrow 'Aktywator' (EXPOM® Sp. z o.o. Krośniewice, Poland). The harrow consisted of five rows with 7 mm diameter tines spaced 12.5 cm apart. The tines were 40 cm long, angled towards the soil surface and had a bent end that penetrated the soil to a depth of 3–5 cm. The harrow was set at ¾ of its maximum aggressiveness and the setting was kept constant throughout.

Measurements

To determine the covering of mixture plants by the soil thrown out with harrow tines, directly after weed harrowing at EM1, FL1 and SL1, the plants of mixture that were visible above the soil surface were counted. The counts were done in four 1 m long neighboring rows with plants in four replicates per plot. The plants were also counted in the control plots. Because it was impossible to distinguish individual plants after cultivation at the later growth stages, two pictures were taken per each harrowed and non-harrowed plot using a digital camera. Each picture covered 0.75 m^2 of area. The picture was then displayed in the Power Point® computer program and covered with a net of 100 regularly distributed dots. The dots which covered the green plant parts in the picture were counted. The data from the counts and from the pictures were used to determine the resistance to the burial index (RBI) (Sobkowicz et al. 2020) calculated according to the following formula:

RBI = a/b, where:

a – the number of mixture plants not covered by the soil just after harrowing at BBCH 10, 11 and 12, or the number of dots covering green plant parts in the picture with the mixture just after harrowing at BBCH 13, 21 and 22;
b – the number of mixture plants in non-harrowed mixture at BBCH 10, 11 and 12, or the number of dots covering green plant parts in the picture with non-harrowed mixture at BBCH 13, 21, 22.

RBI shows, in relative terms, to what extent the mixture plants are resistant to being buried by the soil thrown out with harrow bars during cultivation. RBI = 1 means a total resistance (plants not buried in the soil), while RBI = 0 means no resistance (whole plants buried in the soil). At full maturity of the mixture, the plants were removed by hand from four 1 m long neighboring rows in each plot (0.5 m^2), separated into triticale and lupin and counted. The ears were threshed in a sample thresher, while the pods were shelled by hand. The thousand grain weight was determined on the basis of 500 grains. Mixture grain yields were determined based on the samples collected with the combine harvester after adjusting to a moisture content of 15%.

The weed counts were performed three times during the mixture growth, always on the same day for all treatments. Each count consisted of the weeds which were not covered by the soil thrown out with the harrow, partially covered weeds, and newly emerging weeds. For the first time, the weeds were counted 1–2 days after harrowing at full tillering stage of triticale using a rectangular frame (0.1 m × 2.0 m) placed diagonally on the mixture rows in two replicates per plot. At anthesis of triticale and at harvest (full maturity of the mixture), the density of the weeds was determined using a rectangular frame of 0.5 m × 1.0 m in one replicate per plot. The total aboveground weed biomass was then sampled by hand from that area, dried in a glasshouse and weighted. The aerially-dry matter of the individual weed plant at anthesis of triticale and at full maturity of the triticale-lupin mixture was determined by dividing the aerially-dry matter of weeds by the density of the weeds.

Statistics

Statistical analysis was performed using the Statistica® ver. 13.3 (StatSoft Poland 2017) computer program. All data were analyzed by ANOVA with experimental treatments being fixed factor and years and blocks random factors. The weed data were log10(x+1) transformed to meet the ANOVA assumptions. Post hoc analyzes were performed using Tukey's hsd test (p=0.05). Simple linear regression analysis and Pearson correlation coefficient were calculated on the basis of untransformed data in order to find the relationship between RBI and weed infestation, the plant density of mixture components, and their yields.

Weather

The growing seasons of the triticale-lupin mixture were generally warmer in the experimental years than the long-term average temperature for 1968–2014 (Table 3). Only April 2017 was 0.3 °C cooler. The total rainfall during the growing season (March – August) was lower by 33% in 2015 and by 18% in 2016 than the long-term average, while in 2017 there was 14% more of the rainfall. Very dry August, with only 5.6 mm of rainfall and a peak monthly air temperature of 22.8 °C, was noted in 2015. It did not affect the yield of the mixture because the dry conditions occurred after the grain filling stage of both crops. Furthermore, no visible consequences for plants were observed in April 2015 with only 14.4 mm of rain.

Table 3. Weather data for growing season of triticale-lupin mixture obtained from Agro- and Hydrometeorology Observatory in Agricultural Experiment Station Swojec

Year	March	April	May	June	July	August	March – August rainfall sums
air temperature (°C)							
2015	5.6	9.3	13.9	17.2	20.8	22.8	
2016	4.3	8.8	15.3	19.0	19.9	18.5	
2017	6.9	8.3	14.6	19.1	19.6	19.9	
Average 1968–2014	3.5	8.7	13.9	17.0	18.8	18.2	
rainfall (mm)							
2015	30.8	14.4	30.5	86.0	74.1	5.6	241.4
2016	56.2	27.7	26.4	59.6	105.0	22.6	297.5
2017	34.0	63.8	40.2	65.2	142.6	64.1	409.9
Average 1968–2014	32.5	37.3	58.7	73.9	85.7	72.7	360.8

Results

The resistance of the triticale-lupine mixture to burial in harrow-thrown soil increased with growth stage but decreased with intensity of cultivation (Fig. 1). Repeated cultivations had a more adverse effect on plants resulting in the lowest RBI in the TL2 and BT3 treatments in the experiment, while the SL1, BT1 and FT1 treatments did not differ in RBI. Two harrowings at the third leaf (TL2) and at the beginning of triticale tillering (BT2) significantly reduced RBI while at the full maturity of the mixture three harrowings were needed to reduce RBI compared to the plots with a single cultivations at those treatments.

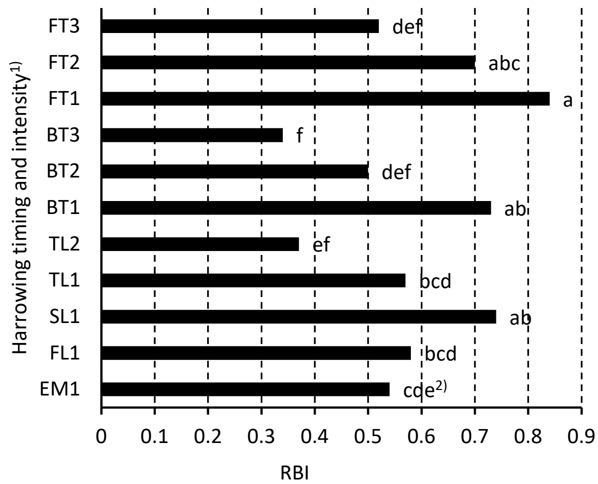

Fig. 1. Resistance to burial index (RBI) of triticale-lupin mixture. Means averaged over 2015–2017.[1)] Letters to the left of the vertical axis indicate growth stages of triticale while numbers denote the number of passes with a harrow per plot; EM=plant emergence, FL=first leaf unfolded, S=second leaf unfolded, TL=third leaf unfolded; BT=beginning of tillering; FT=full tillering; [2)]Bars sharing a common letter are not significantly different at the 5% probability level.

Dicotyledonous weeds accounted for 71% of the total density of weeds. Three weeds dominated during experimental years: lamb's quarters (*Chenopodium album* L.), field pansy (*Viola arvensis* Murr.) and barnyard grass (*Echinochloa crus-galli* (L.) P.Beauv.). Each year the first flush of weeds emerged in late April when triticale had 2–3 unfolded leaves. Before harrowing in TL1 and TL2, most of the weed seedlings had no more than two true leaves and there were many weeds at the cotyledon stage of growth.

The weed counts at full tillering of triticale show that the later the harrowing date, the fewer weeds there were (Table 4). The counts were done 1–2 days after the last cultivations (FT1–FT3) in the experiment, in mid-May, approximately a month after the first cultivation event (EM1). Therefore, the high density of the weeds in EM1 treatment was partially the result of harrow-stimulated seed germination, while the weeds counted in FT1–FT3 treatments were only those which were resistant to a complete cover by soil. One can speculate that there is a continuum between the two cases with respect to the density of weeds in other treatments.

At triticale anthesis there were more weeds in CP and EM1 than in other treatments, except for FT1 (Table 4). Single cultivations conducted between the first leaf and the beginning of triticale tillering were sufficient for a significant reduction in the weed density compared to CP by 43%–63%. Three harrow passes at the beginning of tillering (BT3) that reduced the density of the weeds by 69% were the most detrimental to the weeds. There were no significant differences in the density of weeds at the harvest of the triticale-lupin mixture.

At the anthesis of triticale FL1 and TL1 had 73% and 70% less weed biomass, respectively, than CP treatment (Table 4). Two and three cultivations were required at the beginning of triticale tillering (BT2, BT3) to decrease the biomass of the weeds, while the weed biomass in FT1–FT3 did not differ significantly from that of CP. At the harvest of the triticale-lupin mixture only FL1 and BT3 treatments significantly reduced the biomass of the weeds, by 64% and 57%, respectively, compared to CP.

Table 4. The effect of weed harrowing on the weed density and the weed biomass during growth of triticale-lupin mixture. Means averaged over 2015–2017.

Harrowing timing and intensity	Weed density (plants m^{-2})			Aerially-dry matter of weeds (g m^{-2})	
	full tillering of triticale	anthesis of triticale	harvest	anthesis of triticale	harvest
CP[1)]	(131) 2.12 a[2,3)]	(88) 1.95 a	(65) 1.82 a	(56) 1.76 a	(153) 2.19 a
EM1	(133) 2.13 a	(90) 1.96 a	(53) 1.74 a	(40) 1.62 ab	(85) 1.93 abc
FL1	(74) 1.88 ab	(50) 1.70 bc	(50) 1.71 a	(15) 1.22 b	(55) 1.75 c
SL1	(61) 1.79 abc	(50) 1.70 bc	(47) 1.68 a	(23) 1.38 ab	(75) 1.88 abc
TL1	(52) 1.72 bc	(33) 1.53 cd	(42) 1.63 a	(17) 1.27 b	(72) 1.86 abc
TL2	(31) 1.51 cd	(37) 1.57 bcd	(46) 1.67 a	(23) 1.39 ab	(82) 1.92 abc
BT1	(67) 1.83 abc	(47) 1.69 bc	(43) 1.64 a	(30) 1.50 ab	(100) 2.00 abc
BT2	(31) 1.50 cd	(30) 1.49 cd	(36) 1.57 a	(17) 1.25 b	(78) 1.90 abc
BT3	(21) 1.34 d	(27) 1.44 d	(38) 1.59 a	(16) 1.23 b	(66) 1.83 bc
FT1	(50) 1.71 bc	(61) 1.79 ab	(48) 1.69 a	(36) 1.56 ab	(144) 2.16 ab
FT2	(21) 1.34 d	(41) 1.62 bcd	(43) 1.64 a	(32) 1.52 ab	(144) 2.16 ab
FT3	(15) 1.19 d	(31) 1.50 cd	(47) 1.68 a	(25) 1.42 ab	(110) 2.04 abc

[1)]Letters in the first column indicate growth stages of triticale while numbers denote the number of passes with a harrow per plot; CP=non-harrowed control plots; EM=plant emergence; FL=first leaf unfolded; SL=second leaf unfolded; TL=third leaf unfolded; BT=beginning of tillering; FT=full tillering; [2)]Data were log10(x+1) transformed before ANOVA and means are presented in the table together with back-transformed means in pharentheses; [3)]Means within column followed by a common letter are not significantly different at the 5% probability level

At triticale anthesis, the average biomass of the individual weed in the FT3 treatment was 3.3 times higher than that in FL1, while at full maturity of the mixture, the FT2 treatment had 2.2 and 2.7 times higher biomass of the individual weed than the treatments EM1 and FL1, respectively (Table 5).

Table 5. Effect of weed harrowing on aerially-dry matter of individual weed plant at anthesis of triticale and at full maturity of triticale-lupin mixture. Means averaged over 2015–2017.

Harrowing timing and intensity	Aerially-dry matter of individual weed plant (g)	
	anthesis of triticale	harvest
CP[1)]	(0.71) 0.23 ab[2,3)]	(2.4) 0.53 abc
EM1	(0.62) 0.21 ab	(1.6) 0.42 bc
FL1	(0.36) 0.13 b	(1.3) 0.36 c
SL1	(0.58) 0.20 ab	(1.7) 0.44 abc
TL1	(0.68) 0.23 ab	(1.9) 0.46 abc
TL2	(0.82) 0.26 ab	(1.8) 0.45 abc
BT1	(0.71) 0.23 ab	(2.4) 0.53 abc
BT2	(0.70) 0.23 ab	(2.2) 0.51 abc
BT3	(0.78) 0.25 ab	(1.9) 0.46 abc
FT1	(0.67) 0.22 ab	(3.1) 0.61 ab
FT2	(0.85) 0.27 ab	(3.5) 0.65 a
FT3	(1.18) 0.34 a	(2.4) 0.53 abc

[1)]Letters in the first column indicate growth stages of triticale while numbers denote the number of passes with a harrow per plot; CP=non-harrowed control plots, EM=plant emergence, FL=first leaf unfolded, SL=second leaf unfolded, TL=third leaf unfolded; BT=beginning of tillering; FT=full tillering; [2)]Data were log10(x+1) transformed before ANOVA and means are presented in the table together with back-transformed means in pharentheses; [3)]Means within column followed by a common letter are not significantly different at the 5% probability level

There was no linear relationship between the resistance to burial index (RBI) and the density of weeds at full maturity of the triticale-lupin mixture, but a positive relationship was found between RBI and the biomass of the weeds (Fig. 2).

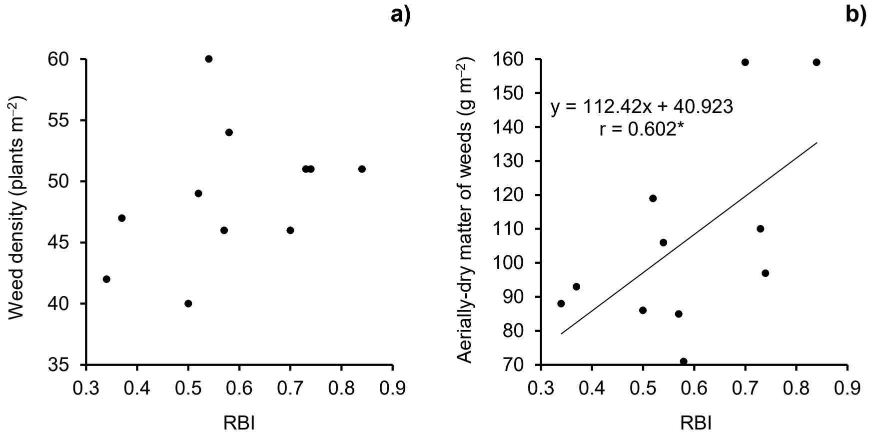

Fig. 2. The linear relationship between RBI of triticale-lupin mixture and a) weed density and b) aerially-dry matter of weeds at the harvest. Regression equation with line and Pearson correlation coefficient (r), is shown when r is significant (* – at 0.05 probability level, n=11). The points represent treatment means of untransformed data averaged over 2015–2017.

The density of plants, the thousand grain weight and the triticale grain yield were unaffected by the weed harrowing (Table 6). Lupin was slightly more prone to disturbance with a harrow. Its plant density was 29% lower in BT3 treatment compared to CP at full maturity of the mixture, but no yield penalty was observed. Lupin compensated for this plant reduction by increasing some yield components other than thousand grain yield which was stable across treatments.

Table 6. The effect of weed harrowing on the plant density, thousand grain weight and grain yield of triticale and lupin. Means averaged over 2015–2017.

Harrowing timing and intensity	Triticale			Lupin		
	Plants m^{-2}	Thousand grain weight (g)	Grain yield (t ha^{-1})	Plants m^{-2}	Thousand grain weight (g)	Grain yield (t ha^{-1})
CP[1)]	99 a[2)]	36.0 a	1.41 a	52 a	104 a	0.81 a
EM1	100 a	36.0 a	1.44 a	41 ab	107 a	0.82 a
FL1	97 a	35.1 a	1.16 a	49 ab	117 a	0.84 a
SL1	92 a	34.3 a	1.31 a	47 ab	117 a	0.88 a
TL1	103 a	34.7 a	1.23 a	53 a	108 a	0.84 a
TL2	102 a	35.3 a	1.22 a	44 ab	108 a	0.74 a
BT1	104 a	33.5 a	1.33 a	47 ab	109 a	0.84 a
BT2	94 a	35.4 a	1.36 a	44 ab	113 a	0.75 a
BT3	96 a	34.0 a	1.10 a	37 b	114 a	0.70 a
FT1	100 a	35.5 a	1.36 a	48 ab	118 a	0.85 a
FT2	95 a	34.3 a	1.31 a	51 ab	110 a	0.86 a
FT3	96 a	33.9 a	1.24 a	42 ab	108 a	0.73 a

[1)]Letters in the first column indicate growth stages of triticale while numbers denote the number of passes with a harrow per plot; CP=non-harrowed control plots; EM=plant emergence; FL=first leaf unfolded; SL=second leaf unfolded; TL=third leaf unfolded; BT=beginning of tillering; FT=full tillering; [2)]Means within column followed by a common letter are not significantly different at the 5% probability level.

No linear relationship was found between RBI and triticale plant density at full maturity of the mixture, as well as grain yield of the cereal. In contrast, there was a positive linear relationship between RBI and the plant density and lupin grain yield (Fig. 3).

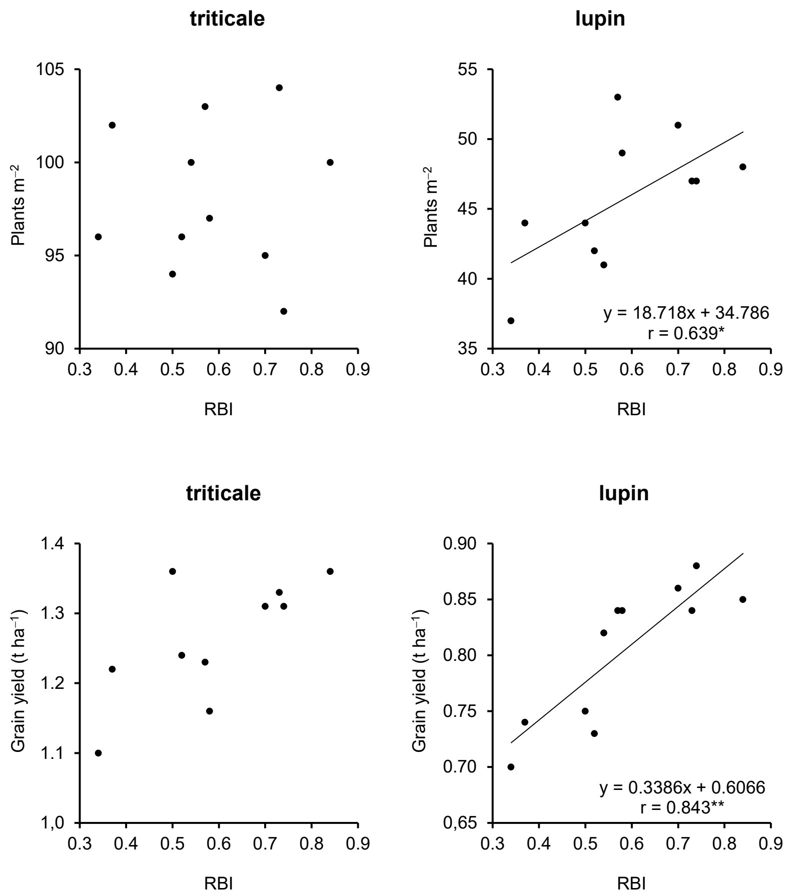

Fig. 3. The linear relationship between resistance to burial index (RBI) of triticale-lupin mixture and the plant density of mixture components at the harvest. Regression equation with line and Pearson correlation coefficient (r), is shown when r is significant (*,** – at 0.05 and 0.01 probability level respectively, n=11). The points represent treatment means of untransformed data averaged over 2015–2017.

Taking into account the triticale-lupin mixture as a whole, no reduction in the plant density was observed at the harvest due to weed harrowing (Table 7). In the BT3 treatment, grain yield was 19% lower than in CP. The percentage of lupin plants in the mixture was not affected by cultivation. The same was true for the contribution of lupin to grain yield.

Table 7. The effect of weed harrowing on the plant density of triticale-lupin mixture at full maturity and grain yield. Means averaged over 2015–2017.

Harrowing timing and intensity	Mixture plant density		Mixture grain yield	
	Plants m^{-2}	Lupin (%)	Yield (t ha^{-1})	Lupin (%)
CP[1)]	151 a[2)]	(36) 36 a	2.22 a	(32) 32 a
EM1	141 a	(32) 34 a	2.26 a	(32) 32 a
FL1	146 a	(35) 36 a	2.00 ab	(35) 34 a
SL1	139 a	(35) 36 a	2.19 a	(35) 34 a
TL1	156 a	(35) 36 a	2.07 ab	(34) 34 a
TL2	146 a	(32) 34 a	1.96 ab	(32) 32 a
BT1	151 a	(33) 35 a	2.17 a	(32) 32 a
BT2	138 a	(34) 36 a	2.11 ab	(31) 32 a
BT3	133 a	(31) 34 a	1.80 b	(33) 34 a
FT1	148 a	(35) 36 a	2.21 a	(35) 34 a
FT2	146 a	(38) 38 a	2.17 a	(35) 34 a
FT3	138 a	(32) 34 a	1.97 ab	(30) 31 a

[1)]Letters in the first column indicate growth stages of triticale while numbers denote the number of passes with a harrow per plot; CP=non-harrowed control plots, EM=plant emergence, FL=first leaf unfolded, SL=second leaf unfolded, TL=third leaf unfolded; BT=beginning of tillering; FT=full tillering; [2)]Means within column followed by a common letter are not significantly different at the 5% probability level; [3)]Percentage data were arc sine transformed before ANOVA and the means are presented in the table and back-transformed means are presented in pharentheses.

Discussion

There are a few possible outcomes of the experiments with weed harrowing in the crops. The most desirable result is when the harrowing reduces the density and biomass of the weeds without a serious injury to the crop, then due to the decreased weed competition, the yield of the crop increases. The first result was achieved in the study. The weeds were best controlled by a single cultivation conducted at the first leaf of triticale (FL1). It caused a significant reduction in the density and biomass of weeds at the anthesis of triticale and a reduction in weed biomass at the full maturity of the mixture. At FL1 most weeds had not emerged yet, therefore, the cultivation was conducted when they were probably at the “white-thread” (Kurstjens et al. 2000) phase of growth, e.g., when they germinated but still grow below soil surface. The subsequent flush of the weeds that appeared after cultivation in FL1 was outcompeted by the mixed species, which was demonstrated by the smallest average weight of individual weed plant in that treatment at the harvest of the mixture. Johnson and Holm (2010) also observed a similar suppressive effect of pea on newly emerging weeds after the mechanical weed control. Kurstjens et al. (2000) concluded that harrowing at the “white thread” stage of the weeds is the most effective way of their control because the implement uproots germinating weeds more effectively than the weeds which form seedlings. The other research reports that spring-tine harrowing decreases weed infestation when the weed seedlings are small, have cotyledons or maximum 1–2 leaves (Lundkvist 2009, Pannacci et al. 2017a, Gerhards et al. 2021) and do not exceed 2.5 cm in size (Kouwenhoven 1997). In the present study, those stages of weeds were observed at the third leaf of triticale (TL1), but a single cultivation at that stage was less effective than that conducted in FL1 in terms of weed biomass at the harvest. Delaying single harrowing until the beginning and full tillering of triticale (BT1, FT1) was ineffective due to the continuously increasing weed resistance arising from the increasing weed size. The present research is in disagreement with a study by Barberi et al. (2000) who suggested that all dominant weeds should emerge before weed harrowing. In their study, the density and growth stage of weeds were not important factors for successful weed control in wheat. They used finger harrow at tillering and at the stem elongation of the cereal.

A significant positive correlation between RBI and weed biomass at the harvest means that the selectivity of harrowing was generally poor and the resistance of weeds to harrowing increased together with the resistance of the mixture to cultivation. Therefore, wherever weeds were present before the harrowing, some of them were able to survive the disturbance and gain biomass until the harvest, in particular when they were at an advanced growth stage like in FT1–FT3 treatments. This is demonstrated by the high biomass of individual weed plant in treatments FT3 at anthesis and FT2 at the harvest of the mixture. Mohler et al. (2016) imply that the only complete burial of a weed plant in soil prevents it from recovering. They observed that if only a small part of a leaf of lamsb’s quarters was not covered by the soil, there was a very high probability that it would recover from burial.

In our study, the increasing intensity of harrowing by repeating cultivations had relatively weak influence on weeds. A more pronounced effect was observed only after three passes with the harrow at the beginning of triticale tillering (BT3). Pannacci et al. (2017b) and Pardo (2008) observed improved effectiveness of two harrowings performed on the same day than the only one treatment at the tillering stage of cereals. They measured the weed infestation a few weeks after cultivation, thus their results correspond to data at the triticale anthesis stage in this experiment, where there was no difference between one pass and two passes with the harrow.

In the research of Corre-Hellou et al. (2011), the components of the barley-pea mixture were able to utilize soil nitrogen more effectively than sole cropped legume depriving the weeds of that nutrient. The authors also observed a synergistic negative effect of the components of the mixture on the biomass of the weeds that was independent of the initial composition of the mixture. While our experiment was not designed to assess the weed suppressive ability of the triticale-lupin mixture, it was interesting to observe that in CP treatment the high initial density of the weeds substantially decreased during the growth of the mixture, while the biomass of the weeds increased being relatively high at the harvest. It means that only the most aggressive weeds withstood the competition from the canopy of mixed crops which was undisturbed with a harrow. Furthermore, in the absence of mineral fertilizer input, those weeds together with the plants of the mixture preempted inorganic soil N and the other nutrients from the soil, before the roots of less aggressive and later emerging weeds reached them.

Among the components of the mixture, triticale was more resistant than lupin to timing and the intensity of harrowing while maintaining the plant density and grain yield similar to those of CP treatment. This contradicts a previous study in which triticale accompanying oats in the mixture reduced its population after a series of harrowings conducted in a few growth stages (Sobkowicz et al. 2020). Because the type of harrow and its setting were the same as in the previous study, the difference may be attributed to a slower harrow speed (10 km h^{-1} vs. 12 km h^{-1}) or the different soil conditions.

Lupin decreased the plant density in BT3 treatment. The result corresponds to the low RBI value observed for that treatment; however, the plant density reduction did not have any significant consequences for lupin grain yield. On the other hand, unlike triticale, lupin demonstrated a positive relationship between RBI and the plant density and grain yield, which means that lupin's ability to compensate for the plant loss was rather weak. The negative effect of the repeated cultivation at a single growth stage on the population of narrow-leaved lupin was also observed by Jensen et al. (2005), however, contrary to the present research, in that study timing of cultivation was not important.

The analysis of variance showed that three passes with the spring-tine harrow at the beginning of triticale tillering (BT3) decreased the grain yield of the triticale-lupin mixture. The decrease coincides with the relatively low the weed density and the biomass in the BT3 treatment at triticale anthesis, confirming that the harrowing selectivity was poor in this study. The vulnerability of cereals to intense harrowing at the beginning of the tillering stage was also reported in our previous study (Sobkowicz et al. 2020).

Conclusions

In conclusion, considering only the grain yield of the mixture, despite the wide range of timing of the weed harrowing used in our study, the results do not clearly show which time of cultivation is most appropriate. None of the treatment caused an increase in yield, suggesting that weed suppressive effect of mixture was strong and weed control was unnecessary, or that the selectivity of the harrowing was poor and the potential gain in yield from the reduced weed competition was counterbalanced by a yield loss due to the destructive effect of harrowing on the mixture. The lack of a crop response to harrowing in terms of grain yield at high weed densities was also noted for small grain cereals by other authors (Dastgheib 2004, Gerhards et al. 2021, Rasmussen et al. 2010). Dastgheib (2004) argued that a strong wheat pressure on weeds stems from the rapid closure of wheat canopy, while Rasmussen et al. (2010) concluded that in their research, weed competition was insignificant.

Although RBI showed well the immediate effect of harrowing on mixture plants, this and previous study (Sobkowicz et al. 2020) demonstrate no relationship between RBI and the grain yield of small grain cereals. Moreover, one might have expected that mixtures with high RBI provide strong weed suppression, but they do not, as shown by the positive relationship between RBI and weed biomass.

The second aim of the weed control is to prevent the weeds from maturing and producing seeds. Taking into account that harrowing had minimal effect on the performance of the triticale-lupin mixture, this study shows that one pass with spring-tine harrow at the first unfolded leaf of triticale appears to be the appropriate way of controlling the weeds. While the most weeds were not then visible above the soil surface, they were at the "white-thread" stage being vulnerable to the damage with a harrow. However, recognizing this stage of the weed growth will be rather difficult in agricultural practice. The future research should focus more on the weed community and its dynamics at the time when a decision on weed harrowing is to be made. In addition, the effect of weeds that recover from the soil burial and those that emerge after the cultivation on the grain yield of the mixture should be explained.

Our results show that a single or repeated harrowing at only one stage of growth of the triticale-lupin mixture is probably not the optimum way of controlling weeds. Future studies should focus on the efficacy of repeated harrowing at different stages of the growth of the mixture.

References

Alba, O.S., Syrovy, L.D., Duddu, H.S.N. & Shirtliffe, S.J. 2020. Increasing seeding rate and multiple methods of mechanical weed control reduce weed biomass in a poorly competitive organic crop. Field Crops Research 245: 107648. https://doi.org/10.1016/j.fcr.2019.107648

Arlauskienė, A., Šarūnaitė, L., Kadžiulienė, Ž., Deveikytė, I. & Maikštėnienė, S. 2014. Suppression of annual weeds in Pea and Cereal Intercrops. Agronomy Journal 106: 1765–1774. https://doi.org/10.2134/agronj13.0478

Armengot, L., José-Maria, L., Chamorro, L. & Sans, F.X. 2013. Weed harrowing in organically grown cereal crops avoids yield losses without reducing weed diversity. Agronomy for Sustainable Development 33: 405–411. https://doi.org/10.1007/s13593-012-0107-8

Bàrberi, P., Silvestri, N., Peruzzi, A. & Raffaelli, M. 2000. Finger-harrowing of durum wheat under different tillage systems. Biological Agriculture & Horticulture 17: 285–303. https://doi.org/10.1080/01448765.2000.9754850

Bedoussac, L., Journet, E.-P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E.S., Prieur, L. & Justes, E. 2015. Ecological principles underlaying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. Agronomy for Sustainable Development 35: 911–935. https://doi.org/10.1007/s13593-014-0277-7

Bleiholder, H., Buhr, L., Feller, C., Hack, H., Hess, M., Klose, R., Meier, U., Stauss, R., van den Boom, T., Weber, E., Lancashire, P.D., & Munger, P. 2005. Klucz do określania faz rozwojowych roślin jedno- i dwuliściennych w skali BBCH (Compendium of growth stage identification keys for mono- and dicotyledonous plants). Poznań: Instytut Ochrony Roślin - Państwowy Instytut Badawczy. (in Polish).

Boerboom, C.M. & Young, F. 1995. Effect of postplant tillage and crop density on broadleaf weed control in dry pea (*Pisum sativum*) and lentil (*Lens culinaris*). Weed Technology 9: 99–106. https://doi.org/10.1017/S0890037X00023022

Brandsæter, L.O., Mangerud, K. & Rasmussen, J. 2012. Interactions between pre- and post-emergence weed harrowing in spring cereals. Weed Research 52: 338–347. https://doi.org/10.1111/j.1365-3180.2012.00925.x

Cirujeda, A., Melander, B., Rasmussen, K. & Rasmussen, I.A. 2003. Relationship between speed, soil movement into the cereal row and intra-row weed control efficacy by weed harrowing. Weed Research 43: 285–296. https://doi.org/10.1046/j.1365-3180.2003.00345.x

Coleman, G.R.Y, Stead, A., Rigter, M.P., Xu, Z., Johnson, D., Brooker, G.M., Sukkarieh, S. & Walsh, M.J. 2019. Using energy requirements to compare the suitability of alternative methods for broadcast and sitespecific weed control. Weed Technology 33: 633–650. https://doi.org/10.1017/wet.2019.32

Corre-Hellou, G., Dibet, A., Hauggaard-Nielsen, H., Crozat, Y., Gooding, M., Ambus, P., Dahlmann, C., von Fragstein, P., Pristeri, A., Monti, M. & Jensen, E.S. 2011. The competitive ability of pea-barley intercrops against weeds and the interaction with crop productivity and soil N availability. Field Crops Research 122: 264–272. https://doi.org/10.1016/j.fcr.2011.04.004

Dastgheib, F. 2004. Optimising tine weeding in organic wheat. New Zealand Plant Protection 57: 41–44. https://doi.org/10.30843/nzpp.2004.57.6939

Drews, S., Neuhoff, D. & Köpke, U. 2009. Weed suppression ability of three wheat varieties at different row spacing under organic farming conditions. Weed Research 49: 526–533. https://doi.org/10.1111/j.1365-3180.2009.00720.x

EC 2014. Common catalogue of varieties of agricultural plant species - 33rd complete edition. https://eurlex.europa.eu/legalcontent/EN/TXT/?uri=OJ:C:2014:450: TOC. Accessed 4 April 2022.

García-Martín, A., López-Bellido, R.J. & Coleto, J.M. 2007. Fertilization and weed control effects on yield and weeds in durum wheat grown under rain-fed conditions in a Mediterranean climate. Weed Research 47: 140–148. https://doi.org/10.1111/j.1365-3180.2007.00547.x

Gerhards, R., Späth, M., Sökefeld, M., Peteinatos, G.G., Nabout, A. & Ayala, V.R. 2021. Automatic adjustment of harrowing intensity in cereals using digital image analysis. Weed Research 61: 68–77. https://doi.org/10.1111/wre.12458

Hauggaard-Nielsen, H., Ambus, P. & Jensen, E.S., 2001. Interspecific competition, N use and interference with weeds in pea-barley intercropping. Field Crops Research 70: 101–109. https://doi.org/10.1016/S0378-4290(01)00126-5

Hauggard-Nielsen, H., Andersen, M.K., Jørnsgaard, B. & Jensen, E.S. 2006. Denisty and relative frequency effects on competitive interactions and resource use in pea-barley intercrops. Field Crops Research 70: 101–109.

Haymes, R. & Lee, H. C. 1999. Competition between autumn and spring planted grain intercrops of wheat (*Triticum aestivum*) and field bean (*Vicia faba*). Field Crops Research 62: 167–176. https://doi.org/10.1016/S0378-4290(99)00016-7

Hofmeijer, M.A.J., Melander, B., Salonen, J., Lundkvist, A., Zarina, L. & Gerowitt, B. 2021. Crop diversification affects weed communities and densities in organic spring cereal fields in northern Europe. Agriculture, Ecosystems & Environment 308: 107251. https://doi.org/10.1016/j.agee.2020.107251

Jensen, R.K., Rasmussen, J. & Melander B. 2004. Selectivity of weed harrownign in lupin. Weed Research 44: 245–253. https://doi.org/10.1111/j.1365-3180.2004.00396.x

Johnson, E.N. & Holm, F.A. 2010. Pre-emergence mechanical weed control in field pea (*Pisum sativum* L.). Canadian Journal of Plant Science 90: 133–138. https://doi.org/10.4141/CJPS09049

Kouwenhoven, J.K. 1997. Intra-row mechanical weed control - possibilities and problems. Soil & Tillage Research 41: 87–104. https://doi.org/10.1016/S0167-1987(96)01076-8

Kurstjens, D.A.G., Perdok, U.D. & Goense, D. 2000. Selective uprooting by weed harrowing on sandy soils. Weed Research 40: 431–447. https://doi.org/10.1046/j.1365-3180.2000.00205.x

Lötjönen,T. & Mikkola, H. 2000. Three mechanical weed control techniques in spring cereals. Agricultural and Food Science in Finland 9: 269–278. https://doi.org/10.23986/afsci.5668

Lundkvist, A. 2009. Effects of pre- and post-emergence weed harrowing on annual weeds in peas and spring cereals. Weed Research 49: 409–416. https://doi.org/10.1111/j.1365-3180.2009.00718.x

Malézieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D., Ozier-Lafontaine, H., Rapidel, B., de Tourdonnet, S. & Valantin-Morison, M. 2009. Mixing plant species in cropping systems: concepts, tools and models. Agronomy for Sustainable Development 29: 43–62. https://doi.org/10.1051/agro:2007057

McCollough, M.R., Gallandt, E.R., Darby, H.M. & Molly, T. 2020. Band sowing with hoeing in organic grains: I. Comparisons with alternative weed management practices in spring barley. Weed Science 68: 285–293. https://doi.org/10.1017/wsc.2019.64

Melander, B., Rasmussen, I.A. & Bàrberi, P. 2005. Integrating physical and cultural methods of weed control - examples from European research. Weed Science 53: 369–381. https://doi.org/10.1614/WS-04-136R

Mertens, S.K. & Jansen, J. 2002. Crop planting pattern, and mechanical weeding in wheat. Weed Science 50: 748–756. https://doi.org/10.1614/0043-1745(2002)050[0748:WSPCPP]2.0.CO;2

Mohler, C.L., Iqbal, J., Shen, J. & DiTommaso, A. 2016. Effect of water on recovery of weed seedlings following burial. Weed Science 64: 285–293. https://doi.org/10.1614/WS-D-15-00130.1

Pannacci, E., Lattanzi, B. & Tei, F. 2017a. Non-chemical weed management strategies in minor crops: A review. Crop Protection 96: 44–58. https://doi.org/10.1016/j.cropro.2017.01.012

Pannacci, E. & Tei, F. 2014. Effects of mechanical and chemical methods on weed control, weed seed rain and crop yield in maize, sunflower and soyabean. Crop Protection 64: 51–59. https://doi.org/10.1016/j.cropro.2014.06.001

Pannacci, E., Tei, F. & Guiducci, M. 2017b. Mechanical weed control in organic winter wheat. Italian Journal of Agronomy 12: 336–342. https://doi.org/10.4081/ija.2017.900

Pardo, G., Cirujeda, A., Aibar, J., Cavero, J. & Zaragoza, C. 2008. Weed harrowing in winter cereal under semi-arid conditions. Spanish Journal of Agricultural Research 6: 661–670. https://doi.org/10.5424/sjar/2008064-358

Poggio, L.S. 2005. Structure of weed communities occurring in monoculture and intercropping of field pea and barley. Agriculture, Ecosystems & Environment 109: 48–58. https://doi.org/10.1016/j.agee.2005.02.019

Ranaldo, M., Carlesi, S., Costanzo, A. & Bàrberi, P. 2020. Functional diversity of cover crop mixtures enhances biomass yield and weed suppression in a Mediterranean agroecosystem. Weed Research 60: 96–108. https://doi.org/10.1111/wre.12388

Rasmussen, J. 1993. Yield response models for mechanical weed control by harrowing at early crop growth stages in peas. Weed Research 33: 231–240. https://doi.org/10.1111/j.1365-3180.1993.tb01937.x

Rasmussen, J., Mathiasen, H. & Bibby, B.M. 2010. Timing of post-emergence weed harrowing. Weed Research 50: 436–446. https://doi.org/10.1111/j.1365-3180.2010.00799.x

Rueda-Ayala, V.P., Rasmussen, J., Gerhards, R. & Fournaise, N.E. 2011. The influence of post-emergence weed harrowing on selectivity, crop recovery and crop yield in different growth stages of winter wheat. Weed Research 51: 478–488. https://doi.org/10.1111/j.1365-3180.2011.00873.x

Rydberg, T. 1993. Weed harrowing - driving speed at different stages of development. Swedish Journal of Agricultural Research 23: 107–113.

Sjursen, H., Brandsæter, L.O. & Netland, J. 2012. Effects of repeated clover undersowing, green manure ley and weed harrowing on weeds and yields in organic cereals. Acta Agriculturae Scandinavica B, Soil and Plant Science 62: 138–150. https://doi.org/10.1080/09064710.2011.584550

Sobkowicz, P., Tendziagolska, E. & Łagocka, A. 2020. Response of oat-triticale mixture to post-emergence weed harrowing. Acta Agriculturae Scandinavica B, Soil and Plant Science 70: 307–317. https://doi.org/10.1080/09064710.2020.1727562

StatSoft Poland 2017. TIBCO™ Statistica®, computer package ver. 13.3.

Steinmann, H.-H. 2002. Impact of harrowing on the nitrogen dynamics of plants and soil. Soil & Tillage Research 65: 53–59. https://doi.org/10.1016/S0167-1987(01)00278-1

Wilson, B.J., Wright, K.J. & Butler, R.C. 1993. The effects of different frequencies of harrowing in the autumn or spring on winter wheat, and on the control of *Stellaria media* (L.) vill., *Galium aparine* L. and *Brassica napus* L. Weed Research 33: 501–506. https://doi.org/10.1111/j.1365-3180.1993.tb01966.x