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Effect of annually repeated weed harrowing against *Chenopodium album* (L.) in organically grown spring cereals

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Spring-tine harrowing is a common physical weed control practice employed in organic cereal cropping. The effects of harrowing treatments on weeds and crop yield were studied in a field experiment of organically grown spring cereals during 2018–2020. The objective was to demonstrate the feasibility of weed harrowing to enhance overall weed management in organic cropping in Finland. Single post-emergence weed harrowing, with or without cover crop drilling, at the 2–4 crop leaf stage was compared with a combined pre- and post-emergence weed harrowing. Treatments were repeated in the same plots for three years and weed occurrence was assessed prior to harrowing, two weeks later and at harvest time. *Chenopodium album* was the predominant weed species in all years. Although harrowing effectively reduced the weed abundance, which was best with the double treatment, the yield response in terms of quantity and quality was negligible. Even so, weed harrowing in cereal years is recommended to suppress weed proliferation in crop rotation.

Key words: CHEAL, mechanical weed control, organic farming, spring barley, spring wheat

Introduction

Spring-tine (flex-tine) harrowing is one of the most widely and thoroughly studied methods for mechanical weed control in cereals (Koch 1964, Rasmussen 1992, Rydberg 1994, Auskalnis and Auskalniene 2008, Rueda-Ayla et al. 2011, Brandsæter et al. 2012). Weed harrowing is highly feasible for organic cropping but could also be applied as an integrated weed management (IWM) option in conventional farming. However, the effect of harrowing on annual weeds in spring cereals is frequently less than that of herbicides (Lötjönen and Mikkola 2000, Armengot et al. 2013).

Detailed studies on weed harrowing in cereals include specifications for timing, machinery and its settings, number of passes, driving speed, harrowing direction, and mechanism of control, in general resulting in varying effects on weeds in different soil types and moisture conditions, crop damage and yield response (Wilson et al. 1993, Rydberg 1994, Rasmussen and Svenningsen 1995, Cirujeda et al. 2003, Sobkowicz et al. 2020). Therefore, instructions and recommendations for efficient weed harrowing are readily available to adjust and apply according to prevailing conditions.

Typically, annual broad-leaved weed species are the main targets of weed harrowing (Wilson et al. 1993, Rasmussen et al. 2010) and the timing of harrowing should strike a balance between susceptibility of weed seedlings and avoidance of crop damage (Hansen et al. 2007, Lundkvist 2009). Knowledge about weed control efficacy and yield response is available from field experiments with cereals in the Nordic countries, where pre-emergence ("blind harrowing"), post-emergence weed harrowing and their combinations have been studied (Lötjönen and Mikkola 2000, Rasmussen and Rasmussen 2000, Lundkvist 2009, Brandsæter et al. 2012, Stenerud et al. 2015). However, results have not been consistent, depending on target weed species, soil type, crop competition and time and subject of assessment.

Globally, fat-hen, or common lambsquarters (*Chenopodium album* L., EPPO code CHEAL), is of notable economic importance due to its' reproductive capacity, seed dormancy, persistence in the soil seed bank, ability to germinate and grow under a wide range of environmental conditions, and abiotic stress tolerance (Bassett and Crompton 1978, Bajwa et al. 2019). In Finland, *C. album* is one of the most frequent and troublesome annual weed species in organic spring cereals (Salonen et al. 2001, 2011). *Chenopodium album* thrives under dry conditions (Maganti et al. 2005), but under favorable conditions spring cereals are strong competitors against *C. album* due to their rapid development during early growth stages (Erviö 1972).

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Competitive ability of the crop plays a central role in weed management, both from an annual and a long-term perspective (Lundkvist et al. 2008). It has been hypothesized that crop competition could be increased, and consequently weed biomass decreased, by sowing cover crops in cereal stands, but this has not been fully supported by the results from the field experiments under northern European conditions (Rasmussen et al. 2006, Sjursen et al. 2012, Stenerud et al. 2015, Salonen and Ketoja 2020).

The objective of this three-year field experiment was to demonstrate and promote the feasibility of weed harrowing by providing farmers research results that support their weed management decision-making in organic spring cereals . Weed surveys in Finland (Salonen et al. 2011, Salonen et al. 2013, Hofmeijer et al. 2021) indicated that weed harrowing is a rarely adopted IWM strategy. However, the need for direct weed control in organically grown spring cereals is apparent because the biomass production of weeds is much higher than in conventional cropping (Salonen et al. 2011). By repeating the weed harrowing operations in the same field plots for three years we expected to record a long-term additive effect of mechanical weed control. Thus, the most comprehensive assessments were carried out in the third year of field experimentation. Cover crops were sown simultaneously at post-emergence weed harrowing each year to examine their potential in suppressing the growth of annual weeds.

Material and methods

The effects of harrowing treatments on weeds and crop yield were studied in organically grown spring cereals at the Mustiala Campus of the Häme University of Applied Sciences (N 60° 49’, E 23° 46’) during 2018–2020. The field experiment was in the same position for three years and was arranged in a randomized complete block design with four replicates. The plot size was 9 m × 100 m and normal farm machinery was used for cropping operations. Meteorological data were obtained from a nearby observatory in Jokioinen to describe weather conditions over the course of experiments (Table 1, Fig. 1).

Table 1. Accumulation of effective temperature sum (ETS, Day Degrees, base +5 °C) and precipitation sum between operation intervals during 2018–2020. Source: Finnish Meteorological Institute, Jokioinen Observatory.

Year	Temperature	Precipitation
Operation intervals	DD, °C	mm
2018		
Sowing_Weed harrowing, post	144	0
Weed harrowing_Weed count 2[1]	N.A.	N.A.
Weed harrowing_Weed sampling[2]	989	98.1
Weed harrowing_Crop Harvest	1064	119.8
2019		
Sowing_Weed harrowing, post	107	31.1
Weed harrowing_Weed count 2[1]	50	31.9
Weed harrowing_Weed sampling[2]	809	138.7
Weed harrowing_Crop Harvest	896	176.3
2020		
Sowing_Weed harrowing, post	130	25.4
Weed harrowing_Weed count 2[1]	167	11.8
Weed harrowing_Weed sampling[2]	894	173.1
Weed harrowing_Crop Harvest	907	173.1

[1]Weed counting approx. two weeks after weed harrowing (see Table 2); N.A. = not assessed;
[2]Weed sampling close to the harvest time.

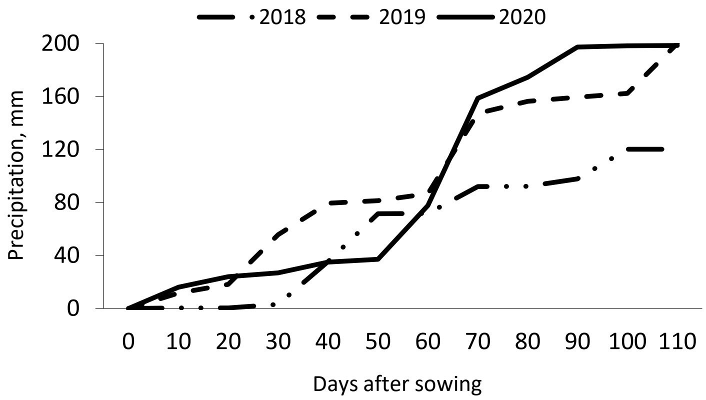

Fig. 1. Cumulative rainfall (mm) at 10-days intervals after sowing during 2018–2020.
Data Source: Finnish Meteorological Institute, Jokioinen Observatory

Preceding crops in the experimental field, still under conventional cropping, were field pea (*Pisum sativum* L.) in 2016 and winter wheat (*Triticum aestivum* L.) in 2017. The soil type was sandy clay and the field was ploughed every autumn to a depth of 20 cm. The seedbed preparation prior sowing was carried out with a S-tine seedbed harrow. The same harrow was used to incorporate cow slurry one day after its application. The slurry was spread on the soil surface of the experimental area each year, approximately corresponding to 50 kg N ha^{-1} available for plants.

The two-year transition period, 2018–2019, from conventional cropping to organic cropping was initiated with spring barley (*Hordeum vulgare* L., cultivar ´Elmeri´ at a typical seeding rate of 500 viable seeds m^{-2}) followed with spring wheat (*T. aestivum* L., cultivar ´Helmi´ at a seeding rate of 600 viable seeds m^{-2}) in 2020. Cereals were sown at a row spacing of 12.5 cm to a depth of 4–5 cm. The calendar time of field operations, adapted to weather conditions, varied among years (Table 2).

Table 2. Diary of field operations in the experimental field during 2018–2020

Operation	Year		
	2018	2019	2020
Shallow seedbed harrowing	11 May	25 Apr	27 Apr
Spreading of slurry	15 May	27 Apr	4 May
Seedbed harrowing	16 May	29 Apr	6 May
Sowing	16 May	30 Apr	6 May
Weed harrowing, pre (Trmnt. 3)	22 May	14 May	21 May
Weed count 1	29 May	22 May	2 Jun
Weed harrowing, post (Trmnt. 2-4)	29 May	22 May	3 Jun
Weed count 2	N.A.[1]	31 May	17 Jun
Weed sampling	15 Aug	7 Aug	19 Aug
Crop Harvest	22 Aug	15 Aug	20 Aug
Growing time of crop, days	103	112	115

[1]Not assessed

Three weed harrowing treatments and an untreated control plot were included in the protocol (Tables 3 and 4). Weed harrowing was carried out along cereal rows with a flex-tine weeder (HE-VA weeder, www.he-va.com) constructed with six 1.5 m-wide free-floating sections with a total working width of 9 m, equal to a plot width in the experiment. The harrow was equipped with a pneumatic seeder unit for simultaneous drilling during weed harrowing. The driving speed was 6–7 km h^{-1} and the flexible double tines (ø7 mm × 600 mm) in five successive rows were adjusted at an angle to achieve light tillage and weed removal at 1–2 cm depth. At the time of weed harrowing cereal plants were at the 2–4 leaf stage (BBCH 12–14) and the seedlings of annual weeds were between cotyledon stage and 2–4 leaf stage. Weed harrowing settings represented a compromise between efficient weed control and minimized crop damage.

A cover crop mixture was sown in Treatment 4 to enhance competition against weeds. The seed mixture was incorporated into the soil during the weed harrowing operation at the 2–4 leaf stage of cereals. The cover crop mixture consisted of white clover (*Trifolium repens* L., 2 kg ha^{-1}) and Italian ryegrass (*Lolium multiflorum* L., 5 kg ha^{-1}) in 2018 and 2019. A slightly different approach was introduced in 2020, when all plots were undersown with a clover-grass mixture (22 kg ha^{-1}) at weed harrowing, except for the Control (Treatment 1), in which the seed mixture was spread on the soil surface at the time of pre-emergence weed harrowing in Treatment 3. The reason for this procedure was that the crop rotation was planned to continue as grassland for silage in 2021. In Treatment 4, honey flower (*Phacelia tanacetifolia* L., 0.5 kg ha^{-1}) was added as an annual cover crop in the clover-grass mixture in 2020.

The occurrence of weeds and the effect of weed harrowing on weed infestation and crop yield were assessed annually with slightly different protocols in terms of number and size of sample plots in each year. The most comprehensive assessments are available from 2020, when the long-term effect of weed harrowing also became apparent. Weed seedlings were counted immediately before post-emergence weed harrowing and 10–15 days after weed harrowing in sample quadrats of 0.25 m^2 to 1.0 m^2, adapted to the level of weed infestation and availability of staff each year and assessment time. The number of sub-samples from each plot ranged between 6 and 10 quadrats, which were pooled to correspond to measurements per 1 m^2 in the statistical analyses. In 2020, the sample quadrats (50 cm × 50 cm) were positioned in the same position to ensure the accuracy of data when analyzing the weed occurrence among the three assessment times.

The biomass of weeds was assessed close to harvest by cutting the plants at the soil surface and weighing them after air-blow drying at 40 °C for several days. In 2020, we also assessed the biomass of crop and undersown plants from the weed sampling quadrats (50 cm × 50 cm). The biomass results are presented as air-dry weight in g m^{-2}. The crop yield was combine-harvested in the middle of each plot from an area of 500 m^2 (5 m × 100 m). The grain yield was weighed, the moisture content determined and the grain yield (kg ha^{-1}) was adjusted to 15% moisture content. The quality analysis of the spring wheat crop in 2020 included 1000 kernel weight and hectoliter weight.

Statistical analyses

Statistical modeling was based on a complete block design. Data for the years 2018, 2019 and 2020 were analyzed separately using linear mixed models for Gaussian and non-Gaussian data. A non-Gaussian model was used because the underlying data distribution was not normal in some cases. Treatments were considered as a fixed effect and blocks were a random effect. A statistical model was fitted using SAS/GLIMMIX version 9.4 software.

Density of *C. album* (plants m^{-2}) was not Gaussian distributed and therefore was analyzed using a generalized linear mixed model with the assumption of a negative binomial distribution with a logarithmic link function. Density of *C. album* at weed harrowing was added as a covariate variable to the model, for density of *C. album* after weed harrowing in 2019 and in 2020, and for density of *C. album* at harvest in 2019. The covariate variable was omitted from the model of density of *C. album* at harvest in 2020 because of absence of a relationship between density of *C. album* at weed harrowing and at harvest in 2020. The covariate variable was also omitted from the model in 2018 because of absence of data.

C. album biomass was analyzed using a generalized linear mixed model with the assumption of a gamma distribution with a logarithmic link function. Grain yield was approximately Gaussian distributed and was analyzed according to the linear mixed model for a complete block design (Littell et al. 2006).

Model assumptions were assessed by the studentized residuals using boxplots and by plotting studentized residuals against the linear predictor. One outlier from *C. album* biomass data in 2020 and one outlier from density of *C. album* at weed harrowing data in 2019 were omitted because they affected the results and their interpretation negatively.

Results

Chenopodium album was the only abundant weed species that emerged each year in the experimental plots at the time of post-emergence weed harrowing, when the crop had reached the 2–4 leaf stage. Thus, the results primarily focus on the weed harrowing effect against *C. album* on an annual basis over three years. During the growing season, there were other weed species at much lower densities, including annual species *Capsella bursa-pastoris* (L.) Medik., *Fumaria officinalis* L., *Galium spurium* L. and *Thlaspi arvense* L. The perennial species

Cirsium arvense (L.) Scop. and *Elymus repens* (L.) Gould occurred in some patches only and weed harrowing did not disrupt their growth.

The density of *C. album*, assessed at the time of post-emergence weed harrowing, increased substantially from few plants m^{-2} in 2018 to over 300 plants m^{-2} in 2020 (Fig. 2). The pre-emergence weed harrowing alone controlled early emerging *C. album* to a limited extent (Fig. 2). The infestation was most effective up to 70%, in terms of weed density reduction, suppressed with combined pre- and post-emergence weed harrowing (Tables 3 and 4).

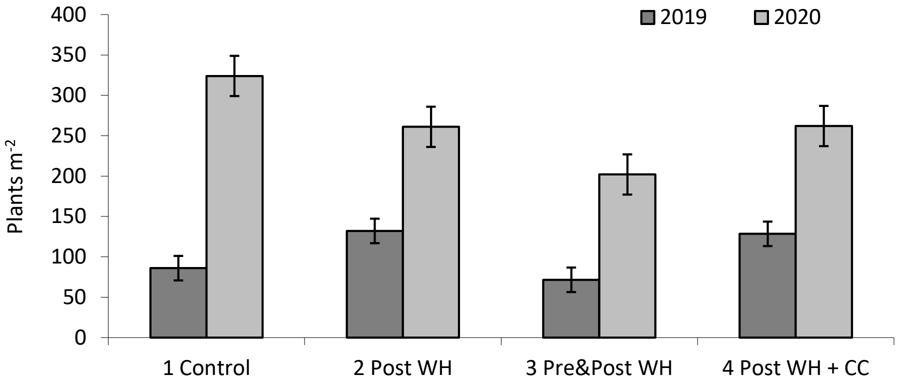

Fig. 2. Number of emerged *C. album* plants (LSMeans with SEM) at the time of post-emergence weed harrowing (WH) at 2–4 leaf stage of crop (CC=with cover crop) in 2019 and 2020

Table 3. Effect of weed harrowing treatments on the density of *C. album* (LSMeans with standard error). Assessments were made approximately two weeks after post-emergence weed harrowing in 2019 and 2020 (see Table 2).

Year	Treatment	CHEAL density[2]	Control effect[3]
		plants m^{-2} (±SE)	%
2019	1 Control	123.9 (11.5)[a]	–
	2 Weed harrow, post	72.0 (6.9)[b]	42
	3 Weed harrow, pre & post	32.3 (4.8)[c]	74
	4 Weed harrow, post & CC[1]	71.5 (7.2)[b]	42
2020	1 Control	211.2 (28.3)[a]	–
	2 Weed harrow, post	101.2 (12.1)[b]	52
	3 Weed harrow, pre & post	68.8 (10.9)[b]	67
	4 Weed harrow, post & CC[1]	94.9 (11.4)[b]	55

[1]Cover crop (CC) was white clover/Italian ryegrass mixture in 2018–2019 and honey flower in 2020; [2]Mean values in each column with different letters within year indicate significant differences between treatments at $p \leq 0.05$; [3]Reduction of *C. album* (CHEAL) density compared to the Control with no weed harrowing.

As observed at harvest time, poor crop competition under the dry conditions of 2018 resulted in few large *C. album* plants, whereas a dense wheat stand in 2020 reduced the biomass production of a much higher number of *C. album* plants (Table 4). The total biomass of *C. album* at harvest in 2020 was about 50% lower after double weed harrowing (Treatment 3) and 40% lower in once-harrowed treatments (Treatments 2&4) compared with the untreated control.

Regarding other weed species in the experiment, weed harrowing reduced their biomass by 40% compared with the control plot (Fig. 3, "WEED"), primarily because of good control of *C. bursa-pastoris* and *T. arvense*, which were at a sensitive seedling stage at the time of post-emergence weed harrowing in 2020. In contrast, the average biomass of *G. spurium* was slightly higher in weed-harrowed plots (19.5 g m^{-2}) compared with the control (15.2 g m^{-2}).

Crop yields were satisfactory for organic farming (Table 4). The crop recovered rapidly from weed harrow passes, except in tractor tramlines. Marked reductions of *C. album* density with weed harrowing treatments in June and total weed biomass in August were, however, not reflected significantly in crop yields. Moreover, market quality parameters 1000 kernel weight and hectoliter weight of spring wheat did not differ among treatments ($p > 0.05$).

Table 4. Effect of weed harrowing treatments on late-summer abundance of *C. album* and crop yield (LSMeans with standard error). Assessments were made each year in August close to the harvest (see Table 2).

Year	Treatment	CHEAL density[2]	CHEAL biomass[2]	Crop yield[2]
		plants m^{-2} (±SE)	g m^{-2} (±SE)	kg ha^{-1} (±SE)
2018	1 Control	5.9 (1.6)^{a}	138.9 (41.8)^{a}	4500 (205)^{a}
	2 Weed harrow, post	8.6 (2.2)^{a}	114.9 (34.0)^{ab}	4373 (205)^{a}
	3 Weed harrow, pre & post	6.4 (2.0)^{a}	47.4 (16.9)^{bc}	4294 (219)^{a}
	4 Weed harrow, post & CC[1]	11.0 (2.7)^{a}	41.9 (12.6)^{c}	4333 (205)^{a}
2019	1 Control	37.6 (6.0)^{a}	N.A.	6286 (248)^{a}
	2 Weed harrow, post	38.1 (6.0)^{a}	N.A.	6329 (248)^{a}
	3 Weed harrow, pre & post	17.8 (3.5)^{b}	N.A.	6019 (248)^{a}
	4 Weed harrow, post & CC[1]	29.0 (4.9)^{ab}	N.A.	6364 (248)^{a}
2020	1 Control	360.0 (34.0)^{a}	63.0 (11.0)^{a}	4014 (207)^{ab}
	2 Weed harrow, post	127.3 (12.8)^{bc}	34.4 (6.0)^{bc}	4213 (207)^{ab}
	3 Weed harrow, pre & post	110.0 (13.0)^{c}	24.1 (4.6)^{c}	3846 (221)^{b}
	4 Weed harrow, post & CC[1]	162.0 (16.0)^{b}	39.3 (6.9)^{b}	4290 (207)^{a}

[1]Cover crop (CC) was white clover and Italian ryegrass mixture in 2018–2019 and honey flower added in undersown clover-grass mixture in 2020. [2]Mean values in each column with different letters within year indicate significant differences between treatments at $p \leq 0.05$.

The crop growth, particularly at early growth stages in 2019 and 2020, was very vigorous, resulting in crop stands that competed well against weeds. The crop stand was particularly sparse and short in 2018, and *C. album* plants were about 20 cm higher than barley, whereas in 2019 and 2020 the height of *C. album* was 10–20 cm lower than the crop height of 90 cm at heading stage. The booting of barley (BBCH stage 41) was delayed for a couple of days both in 2018 and 2019, but not in wheat in 2020 in weed-harrowed plots compared with the control plots. Spring wheat biomass comprised 83% of total vegetative biomass in control plots and 89–90% in weed-harrowed plots (Fig. 3).

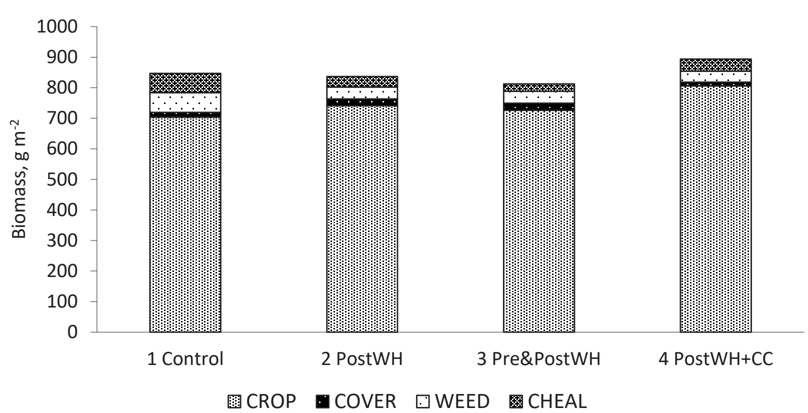

Fig. 3. Effect of weed harrowing (WH) treatments on the biomass shares between different plant groups at harvest time of spring wheat ("CROP") in 2020. "COVER" represents the pooled biomass of undersown clover-grass mixture in all treatments and additionally the cover crop honey flower ("CC" in Treatment 4). "WEED" represents all other weed species except *C. album* (CHEAL).

Clover-grass mixture as a cover crop failed to establish satisfactorily in 2018 and 2019, mainly due to the unfavorable weather conditions in 2018 and dense crop in 2019. In 2020, the undersown clover-grass mixture with honey flower (Treatment 4) succeeded slightly better but corresponded only with 14% of the total biomass of undersown crops and all weed species at harvest (Fig. 3).

Discussion

This study was part of a project promoting the development of organic production chains, from field to fork. Numerous weed species hamper crop production, *C. album* being one of the most common and abundant species in organic spring cereals in Finland (Salonen et al. 2001). By coincidence, the species composition of weeds in our experimental field was dominated by *C. album* in each year. At the time of post-emergence weed harrowing in 2019, *C. album* density, 124 plants m^{-2}, was close to the reported average of 107 plants m^{-2}, for organic spring cereal fields in Finland (Salonen et al. 2011), but the density doubled in 2020, corresponding to 94% of weed seedlings assessed from sample quadrats. The sowing day in 2020 was one week later and the time between sowing and post-emergence weed harrowing was two weeks longer than in 2019, indicating the differences between annual growth conditions and the need for frequent field observations to adjust timing of weed harrowing. In our experiment, weed harrowing was carried out at the end of May or early June, which is typically the emergence period of annual weed species, including *C. album* (Erviö 1981).

The highest total biomass of *C. album* at harvest was recorded in 2018, originating from a small number of tall and heavy individuals thriving in a poorly competitive barley stand. Although the density of *C. album* was much higher in 2020, the total biomass of *C. album* plants was only half that in 2018, but much higher than the reported average, 11.5 g DW m^{-2}, in organic spring cereals in Finland (Salonen et al. 2011).

C. album was most effectively controlled with a combination of pre- and post-emergence weed harrowing, corresponding with results from other studies in the Nordic countries. In Sweden, weed harrowing before crop emergence combined with the post-emergence weed harrowing at the 2–3 leaf stage of cereals resulted in control effects of 35–92%, depending on the weed species (Lundkvist 2009). In Norway, Brandsæter et al. (2012) reported that the average control effect of pre-emergence weed harrowing on *C. album* was 36% and that of post-emergence harrowing was 62% in spring cereals. Furthermore, Stenerud et al. (2015) succeeded in reducing the weed density by 59% and weed biomass by 67% when combining pre- and post-weed harrowing in spring cereals. However, the combination did not provide more long-standing weed suppression than pre- and post-emergence weed harrowing applied alone.

Post-emergence weed harrowing was carried out under good conditions at the 2–4 leaf stage of the crop, as planned each year. However, the time between sowing and weed harrowing differed from 13 DAS in 2018 to 28 DAS in 2020, reflecting marked differences in growth and weather conditions in early spring. Not only the combination, but also the single post-emergence weed harrowing reduced weed density and biomass. Weed seed production is related to weed biomass (Wilson et al. 1995), which implies that annually repeated weed harrowing could reduce the input to the weed seed bank in the long term. The suggestion is not supported by Norwegian studies (Stenerud et al. 2015) in which the seed bank increased after post-emergence weed harrowing with a cover crop during the 4-year study period. Therefore, seed bank dynamics merit more comprehensive studies.

The gain from effective weed control and reduced weed pressure did not result in higher crop yields, thus corresponding with the findings of Auskalnis and Auskaniene (2008) and Gerhards et al. (2020). Overall, the high biomass proportion of the crop compared with weeds and cover crops indicates the superiority of the crop in competition. Presumably the uptake of nitrogen from applied slurry boosted the early growth of cereals. Brandsæter et al. (2012) reported more positive results in hard-packed soils, in which the combination of pre- and post-emergence weed harrowing increased yields in the experiments with a low overall yield level. In general, the effect of weed harrowing on crop yield is not consistent but greatly depends on prevailing conditions – both negative and positive yield responses have been reported (Lötjönen and Mikkola 2000, Armengot et al. 2013).

Each year there was a tendency for lowest yields to be in the plots that were weed-harrowed twice, although cereal plants can recover from physical disturbance (Sobkowicz et al. 2020). Our yield results slightly overemphasize crop damage because the crop was harvested from a 5 m wide mid-strip, which included stamped tractor tracks, rather than a 9 m wide weed-harrowed plot with a higher proportion of non-stamped area. Nevertheless, both soil packing and trampled leaves hampered crop growth. It would have been useful to compare crop biomass from trampled and non-trampled areas. Passing damage included stem shortening and delayed maturity, which were visible throughout the growing seasons in tractor wheel tracks, most clearly in double-harrowed plots. Narrower tractor wheels, or the deployment of tramlines, should be considered; the lack of crop in the tramline would presumably be compensated for by more vigorous crop growth on either side of the tramline (Hamza and Anderson 2005). In addition, technical development of devices and their adjustment is expected to result in more effective and selective harrowing intensity (Gerhards et al. 2020).

The 2018 growing season was extremely challenging in terms of weather conditions. There was very little rainfall in the 32 days after sowing, resulting in extremely poor and uneven emergence of crop and weeds. Erviö's (1972) results from pot trials showed that a dry period at early growth stage of wheat had no significant effect on the growth of *C. album* but reduced the biomass of wheat significantly. Maganti et al. (2005) also demonstrated that *C. album* thrives better under dry conditions than do cereal grains like barley. It can be concluded that sufficient moisture is needed for barley to have a competitive advantage. In general, both drought and extreme wetness, especially early in the season, have been found to be detrimental to barley yield (Hakala et al. 2012). Based on harvested yields and additional costs of weed harrowing, it can be concluded that the economic benefits of weed harrowing were negligible or even negative for each year in this experiment.

The continuous cereal rotation during the years of this field experiment was not typical of organic production. The low density of *C. album* in 2018 was likely a combined consequence of extreme drought and background of conventional cropping in the field. Although spring cereals compete well with weeds, a considerable increase in *C. album* infestation in three years was apparent. Weed suppression with cover crops failed due to poor establishment in 2018 and 2019 and due to relatively low biomass production in 2020. In previous studies, Rasmussen et al. (2006) noted the reduction of weed density but not of weed biomass when including cover crops in a four-year rotation of arable crops. In contrast, ryegrass alone and when combined with clover, significantly suppressed weed biomass by up to 70% in Norwegian studies with organic cereals (Sjursen et al. 2012). Including winter cereals with spring-sown cover crops in the rotation could have a greater potential to compete against annual weeds than spring cereals with cover crops (Salonen and Ketoja 2019).

Conclusions

Combination of pre- and post-emergence weed harrowing resulted in the best control of *C. album* in terms of reduction in plant density and biomass production. However, two passes with a tractor caused crop damage in tramlines, which was visible throughout the growing season, particularly in spring wheat in 2020. Weed harrowing was not economically effective. Nevertheless, continued and repeated weed harrowing in cereals is a potential weed control option in the long term as a component of a management strategy to apply direct methods whenever feasible for crops in rotation.

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