

Intensifying bare fallow strategies to control *Elymus repens* in organic soils

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Perennial weeds are an increasing challenge in organic farming in the Nordic countries. The aim of this study was to compare different tillage methods in the control of *Elymus repens* by using two intensified bare fallow strategies. Two field experiments consisted of three ploughing methods and seven fallow methods. The experiments were carried out in organic soils in Central Finland. The methods applied in the brief fallow before cereal sowing (exp. 1) were not effective enough against *E. repens*. Due to wet weather conditions in the spring the fallow period was limited to two weeks in both years, which did not seem to be enough time. In the late summer fallow after ley (exp. 2), the Kwick-Finn weed-cultivator destroyed *E. repens* very effectively; on average 5% of *E. repens* remained alive in the barley crop in the autumn of the following year. After use of ordinary cultivators 10% of *E. repens* remained alive, after use of the spade harrow 25% and after frequent mowing over 50% remained alive, respectively. As a result of effective *E. repens* control, barley yield was about 1000 kg ha⁻¹ higher than without any fallow. In conclusion, effective control of *E. repens* is achieved with proper machinery and repeated treatments at the optimal time.

Key words: fallowing, Kwick-Finn, mechanical control, organic farming, perennial weed, tillage

Introduction

Perennial weeds are recognised as an increasing challenge in organic farming in the Nordic countries (Salonen et al. 2011, Brandsaeter et al. 2012, Melander et al. 2012). In Finland, *Elymus repens* (L.) Gould is the most abundant perennial weed, but also *Cirsium arvense* L. and *Sonchus arvensis* L. are becoming more common in organic farming (Riesinger 2010, Salonen et al. 2011). Perennial weeds can decrease remarkably amounts of yield in organic cereals and protein crops and hamper harvest operations (Melander 1994, Graglia et al. 2006). The development of non-chemical perennial weed control methods is also essential in conventional farming, since there is an universal need to decrease the use of glyphosate and other herbicides (Melander et al. 2013a).

In organic farming weeds are controlled by a combination of preventive, cultural and direct control methods. Including frequently mowed perennial leys in the crop rotation helps to control *C. arvense* and *S. arvensis*, but *E. repens* often tends to proliferate in old leys (Dock Gustavsson 1994, Graglia et al. 2006, Vanhala et al. 2006). However, most organic farms without livestock cannot utilize the yield of perennial leys, so the crop sequence mainly consists of annual crops. This often leads to increasing problems with perennial weeds. Undersown cover crops and post-harvest mowing after the main crop harvest may help to control perennial weeds (Aronsson et al. 2015, Ringselle et al. 2015a), but cover crops have not always been effective (Brandsaeter et al. 2012).

Traditional bare fallow, which lasts the whole summer, is known to be rather effective against perennial weeds, but it is expensive (one year without crop and requires much work and fuel), it can be harmful to the soil structure, and it can lead to nutrient leaching (Bond & Grundy 2001). There is a need for intensified strategies to be used in fallowing. Intensifying here means achieving a better effect against weeds, less working hours and shorter fallowing time compared to traditional bare fallow.

In principle, bare fallow can be based on four mechanisms: 1) lifting the roots or rhizomes of perennial weeds to the soil surface so that the sun and wind will desiccate them, 2) conducting tillage at compensation points, i.e. applying an exhaustion strategy, 3) cutting weed roots into small pieces and burying the pieces deep in soil or 4) lifting the roots to the soil surface and removing them (Håkansson 1995, Dock Gustavsson 1997, Melander et al. 2013b). In practice, all strategies can be used in the same field depending, for example, on weather conditions and cropping sequences. Equipment that would perfectly execute strategies 1 and 4 is challenging to design (Kristensen et al. 2010). In many situations, the best weed control result can be achieved when strategy 2 is applied. Compensation point (i.e. time, when dry matter weight of roots is at a minimum) have shown to be 3–4 leaves for *E. repens* (Håkansson 1967).

In practice, bare fallow can be implemented using at least five different strategies (estimated duration of fallow period at northern latitudes in parenthesis): 1) brief fallow in spring before crop sowing (2–4 weeks), 2) following during May–June followed by sowing green manure crops (2 months), 3) harvest one silage yield and following after that (late summer fallow) (3 months), 4) bare following the whole summer (5 months) and 5) stubble cultivation after cereal harvest (1–2 months) (Håkansson 1995).

For the tillage of bare fallow, many types of machinery can be used, for example S-tine harrows, tined cultivators, disc harrows/cultivators, rotary cultivators, power harrows and rotary spade harrows (Kristensen et al. 2010, Melander et al. 2012). The Kwick-Finn weed-cultivator (KF-cultivator) is a fairly new type of machinery, specially designed to lift roots of perennial weeds up to the soil surface and thus, increase the efficacy of bare fallow against vegetatively propagating weed species.

Minimal studies have been conducted on the weed control efficacy of the Kwick-Finn or preceding Kwick-Upp cultivator. Jacobsson (2006) examined Kwick-Upp as a stubble cultivation tool after cereal harvest in Sweden. *E. repens* had decreased more than 80%, when two cultivations were performed in autumn and one in spring followed by spring ploughing. Without stubble cultivation, in clay soils, spring ploughing controlled *E. repens* slightly better than autumn ploughing, and in lighter soils the opposite was noted.

In Sweden, Ringselle et al. (2015b) managed to control *E. repens* successfully in loamy soils by means of 1–2 stubble cultivations with a tined cultivator, which was followed by autumn ploughing. Also studies made in Norway and Denmark managed to significantly reduce perennial weeds by means of stubble cultivation (Brandsaeter et al. 2012, Melander et al. 2012). In Finland, stubble cultivation could also be beneficial for the control of perennial weeds if the autumn season is dry and warm (Vanhala et al. 2006). However, very often autumn is too short and wet for repeated tillage to achieve reliable weed control after cereal harvest.

Therefore, we decided to focus on strategies 1 and 3 described above. The main objective was to find out the most effective tillage methods in the control of *E. repens* in brief fallow in spring before cereal sowing (experiment 1) and in late summer fallow when old ley is broken up (experiment 2). Previous crops had been cereals in experiment 1 and ley in experiment 2. We chose three ploughing methods and three non-inverse tillage methods for experiment 1 and five fallow methods for experiment 2. We decided to concentrate on *E. repens*, since it is the most abundant perennial weed in organic farming in Finland.

Material and methods

Two experiments were conducted at the MTT Ruukki Research Station in Central Finland (64° 41, N; 25° 05, E) during the period 2012–2014. Experiment 1 (Brief fallow exp.) was located in the same fixed place for two years. Experiment 2 (Late summer fallow exp.) was transferred to a new location for both years, since the treatments destroyed the ley during the first summer. The fields were not certified organic, but no pesticides or synthetic fertilizers were used during the study. The studies were carried out in peat/organic soils, in which *E. repens* seems to proliferate extremely fast.

The basic idea of the KF-cultivator was developed in Denmark at the beginning of 2000, but currently the machine is being further developed and manufactured by a Finnish company. Goosefoot tines loosen the soil and after that a PTO-driven rotor throws soil and weed roots/ rhizomes into the air (Suppl. Figs. 1 and 2). Since weed roots are lighter than soil, roots will settle on the soil surface, where they are desiccated by the sun and wind. If the weather is not dry, the roots use their energy when they begin to grow again. The manufacturer claims that repeated treatments with the KF-cultivator near the compensation point can destroy perennial weeds also during wet conditions, but it takes a longer time to achieve sufficient results than during dry periods (<http://www.ekotjanst.fi/>).

Experiment 1

In experiment 1, the objective was to compare autumn and spring ploughing to minimum tillage and to the KF-cultivator by measuring their effects on *E. repens* growth and barley yield (Table 1). In the first year, autumn ploughing was not possible, so it was replaced by spring ploughing. Furthermore, we wanted to gain knowledge about the benefits of trashboards and skimmers installed on ploughs (Suppl. Figs. 3 and 4). These implements are used to drop topsoil to the bottom of the furrow. This is assumed to delay emergence of weeds through furrow joints.

In experiment 1, the soil type was carex peat (pH 5.6). Spring barley had been cultivated in that location in the period 2009–2011. Glyphosate was applied previously in autumn 2010 in order to control *E. repens*. In spring 2012–2013 the experimental area was cultivated using treatments described in Table 1 (Suppl. Figs. 1–6). After that the area was fertilised with beef cattle slurry and drilled with spring barley.

Ploughing depth was 22–25 cm and driving speed 5–8 km h⁻¹. The goosefoot tines of the KF-cultivator were set to a depth of 10–12 cm and driving speed was 4–5 km h⁻¹.

The size of experimental plots was 6 × 30 m, to allow for the use of machinery typical on Finnish farms. The number of *E. repens* shoots was counted from both ends of the plots at the beginning of experiment 1 (on 15th May 2012) by using a 2 × 0.25 m² frame. In autumn 2012, experimental plots were harvested and a sample corresponding to a 1 m² area was taken from the swath (2 × 0.5 m²). In autumn 2013, crop samples were taken at both ends of the plots by using a 2 × 0.25 m² frame before the barley harvest. The crop samples were cut to 2–4 cm stubble height by electric scissors. The samples were separated into barley, *E. repens* and other weeds in both years. Dry weight of weeds was measured after oven-drying (+105 °C, 24 h). Barley was harvested by a Wintersteiger-plot combine harvester. Barley hectolitre weights were measured by a chondrometer.

Table 1. Treatments and other farming operations in experiment 1. Treatments were repeated in the same fixed place in 2012 and 2013.

		Treatments						
		1) Spring or autumn ploughing with trashboards	2) Spring ploughing, no implements	3) Spring ploughing with skimmers	4) Spring cultivation with discs or rotary spade harrow (3–4 times)	5) Spring cultivation with KF-cultivator (2 times)	6) Spring cultivation with KF-cultivator (2–3 times)	
Autumn 2011	No cultivations in autumn 2011. Preceding crop in 2011: spring barley.							
	Spring ploughing 24 May	Spring ploughing 24 May	Spring ploughing 24 May	Disc harrow 4 times, 24–30 May	KF-cultivator 2 times, 24–30 May	KF-cultivator, 3 times 24 May–6 June		
Spring 2012	Seedbed harrowing Beef cattle slurry 20 ton ha ⁻¹ (44 kg soluble N ha ⁻¹) and harrowing, 7 June Sowing spring barley (var. “Brage”) 500 seeds m ⁻² , 8 June Barley harvest and weed samples, 18 Sep							
Autumn 2012	Autumn ploughing, 11 Oct	No cultivations in autumn 2012					Autumn ploughing, 11 Oct	
		Spring ploughing 31 May	Spring ploughing 31 May	Rotary spade harrow, 3 times, 20 May–3 June	KF-cultivator 2 times 21–27 May	KF-cultivator 2 times 21–27 May		
Spring 2013	Seedbed harrowing Beef cattle slurry 18 ton ha ⁻¹ (40 kg soluble N ha ⁻¹) and harrowing, 3 June Sowing spring barley (var. “Brage”) 500 seeds m ⁻² , 3 June							
Autumn 2013	Weed samples, 3 Sep Barley harvest, 9 Sep							

Experiment 2

In experiment 2, the aim was to compare the tined cultivator, rotary spade harrow and KF-cultivator in late summer fallow, when old ley is broken up mechanically (Tables 2 and 3). It is known that in old leys rhizomes of *E. repens* grow quite near the soil surface and it is possible to cut rhizomes by frequent shallow cultivations (Håkansson 1995). Usually it is not reasonable to plough the ley in the beginning of fallowing, since ploughing will bury the rhizomes too deep to be controlled mechanically.

In experiment 2, the soil type was carex peat (pH 5.6) in 2012–2013 and coarse sand with high organic content (pH 5.8) in 2013–2014. The experimental field had been used as silage ley (timothy-meadow fescue) for three years when the experiment was started in 2012. In 2012–2013 and 2013–2014 the experiments were located in a different part of the same field.

One silage yield was harvested in June in both years from experimental areas, after which the remaining ley was cultivated using different methods. In 2012, the beginning of cultivations was delayed until mid-July due to rainy weather. In 2013, cultivations were started already in June (Tables 2 and 3). Cultivations were carried out every

2–3 weeks (near the compensation point of *E. repens*) until the beginning of September or October, depending on weather conditions. In the first year of the experiment one pass was made with the KF-cultivator in the following spring before barley sowing, but in the second year, spring cultivation was not carried out. All experimental plots were ploughed in the following spring, fertilized with beef cattle slurry and drilled with spring barley.

There were two different treatments with the KF-cultivator: In treatment 2 the first cultivation was done with the rotary spade harrow to ensure that the KF-cultivator can break the surface of the ley. Treatment 3 was started directly with the KF-cultivator, which succeeded well, as the soil was soft enough. The rotary spade harrow that was used in the experiments was an old Wäertsila Hankmo (3.2 m wide) with six spade axels (Suppl. Fig. 6). The weight of the machine was not enough to break the ley surface with one pass and this was compensated for by working the plots twice during same day. Unfortunately, it was not possible to get a new, heavy and long-bladed rotary spade harrow to use for the experiments. The SMS-tined cultivator (treatment 4) had spring tines with narrow blades in the first year and rigid tines with goosefoot blades in the second year (Suppl. Figs. 7 and 8).

Table 2. Treatments and other farming operations in experiment 2 in 2012–2013

		Treatments					
		1) No bare fallow	2) Rotary spade harrow+ KF-cultivator	3) KF-cultivator	4) Tined cultivator	5) Rotary spade harrow	6) Frequent mowing
		First silage was harvested 20 June					
		Mowing to 5 cm stubble 18 July					
Summer 2012		Spade harrow 20 July	KF-cultivator 19 July, 1 Aug, 17 Aug and 29 Aug (3 times)	KF-cultivator 19 July, 1 Aug, 17 Aug and 29 Aug (4 times)	Tined cultivator with narrow blades 19 July, 1 Aug, 17 Aug and 29 Aug (4 times)	Spade harrow 19 July, 1 Aug, 17 Aug and 29 Aug (8 times)*	Not included 2012
	Second silage was harvested 14 Aug						
Spring 2013		KF-cultivator 1 time, 21 May		KF-cultivator 1 time, 21 May			
		Ploughing the whole experiment at the depth of 23 cm, 27 May					
		Seedbed harrowing 29–30 May					
		Beef cattle slurry 18 ton ha ⁻¹ (40 kg soluble N ha ⁻¹) and harrowing, 29 May					
		Sowing spring barley (var. "Brage") 500 seeds m ⁻² , 30 May					
Autumn 2013		Weed samples 20 Aug					
		Barley harvest 10 Sep					

*Poor tillage performance of the spade harrow was compensated by driving the plots twice during same day.

Table 3. Treatments and other farming operations in experiment 2 in 2013–2014

		Treatments						
		1) No bare fallow	2) Rotary spade harrow + KF-cultivator	3) KF-cultivator	4) Tined cultivator	5) Rotary spade harrow	6) Frequent mowing	
		First silage was harvested 13 June						
Summer 2013		Second silage was harvested 7 Aug	Spade harrow 18 June	KF-cultivator 18 June, 4 July, 23 July, 5 Aug, 22 Aug and 4 Oct (5 times)	KF-cultivator 18 June, 4 July, 23 July, 5 Aug, 22 Aug and 4 Oct (6 times)	Tined cultivator with goosefoot blades 4 July, 24 July, 5 Aug, 22 Aug, 30 Aug and 4 Oct (6 times)	Spade harrow 18 June, 4 July, 23 July, 5 Aug, 22 Aug and 4 Oct (12 times)*	Mowing with rotary crusher 1 July, 23 July, 31 July, 7 Aug, 21 Aug, 3 Sep and 7 Oct (7 times)
Spring 2014		Ploughing the whole experiment at the depth of 23 cm, 26 May						
		Seedbed harrowing, 2–3 June						
		Beef cattle slurry 17 ton ha ⁻¹ (34 kg soluble N ha ⁻¹) and harrowing, 2 June						
		Sowing spring barley (var. "Einar") 500 seeds m ⁻² , 3 June						
Autumn 2014		Weed samples, 25 Aug						
		Barley harvest, 1 Sep						

* = Poor tillage performance of the spade harrow was compensated by driving the plots twice during same day.

Frequent mowing of ley (treatment 6) was included in the experiment in 2013, as some farmers claimed to be able to decrease the amount of *E. repens* that way. This was also noted by Ringselle et al. (2015a). The ley was mown 7 times during July–October, each time the grass reached a height of 10–15 cm. The mowing was conducted using a McConnel horizontal rotary mower and the target stubble height was under 5 cm (Suppl. Fig. 9). The driving speeds, PTO-speeds and working depths are presented in Table 4.

Table 4. Machinery adjustments in experiment 2

	Driving speed	PTO-speed*	Working depths
KF-cultivator	4–5 km h ⁻¹	540–600 min ⁻¹	10–12 cm
SMS-cultivator	8–10 km h ⁻¹	–	10–12 cm
McConnel-mower	6–8 km h ⁻¹	540 min ⁻¹	+ 2–5 cm
Wärtsilä-rotary spade harrow	12–14 km h ⁻¹	–	2–6 cm

The size of experimental plots was 6 × 20 m. The amount of *E. repens* shoots was not counted at the beginning of the experiments, since it would have been very difficult in growing ley. The experimental areas were placed in locations where it could be assumed that *E. repens* was evenly distributed. The plant samples were taken and analysed in a way similar to experiment 1 in 2013 (scissors, 2 × 0.25 m² frame).

The experimental design and statistical models in experiments 1 and 2

The experimental design was a randomized complete block with four replicates and each experimental year was treated as individual, since there were significant interactions between years and treatments. The statistical model was

$$\chi_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij},$$

where μ is the constant, α_i is the treatment factor, β_j is the block factor and ε_{ij} is the error term.

Data about *E. repens* shoot density at the beginning of experiment 1 were not used as a covariate in the statistical model, as there were no statistically significant differences in *E. repens* shoot density ($p = 0.07$). The weed and barley yield data were analysed by ANOVA using the PROC MIXED function of the SAS program (version EG 5.1, SAS Institute Inc., Cary, NC). Model assumptions were checked graphically from the residuals and by means of the UNIVARIATE procedure. There was no need to make transformations to data. Pairwise comparisons were performed using the Tukey-Kramer test.

Weather conditions

The growing season of 2012 was wetter and colder at Ruukki than the long-term average (Table 5). Alternatively, growing seasons 2013–2014 were slightly dryer and clearly warmer compared to the long-term average. Certainly, there were also cold periods (e.g. June 2014) and heavy rains (e.g. July 2014).

Costs

The cost calculations of using the KF-cultivator were based on the standards of the TTS-institute (Palva 2013). The price of a three-metre-wide cultivator was estimated to be 15000 EUR (VAT 0%); lifetime 10 years; residual value 5000 EUR; operating time 100 h year⁻¹ and interest 5%; the price for tractor work including the driver was assumed to be 52 EUR h⁻¹.

Results

Experiment 1

At the beginning of the experiment the abundance of *E. repens* was on average 283 shoots m². The lowest value was 104 shoots m² and the highest 400 shoots m² (N = 48 counting plots). The quantity of *E. repens* can be considered very high and sufficient for the experimental efforts.

None of the methods applied in the experiment decreased the amount of *E. repens* remarkably (Fig. 1). In the first year there were no statistically significant differences between the treatments. The amounts of *E. repens* was 130–200 g DM m² before the barley harvest. According to our observations, a high amount of *E. repens* predisposed cereal to lodging and substantially hampered combining.

Table 5. Weather conditions at Ruukki during 2012–2014 and long-term averages 1981–2010 (Finnish Meteorological Institute)

Month	Rainfall, mm				Growing degree-days, °C			
	2012	2013	2014	1981–2010	2012	2013	2014	1981–2010
May	64	27	46	42	96	213	137	95
June	76	88	31	50	204	336	199	244
July	58	60	115	77	291	310	424	338
August	83	47	44	71	246	291	310	263
September	52	31	18	50	121	175	152	113
Sum	332	255	254	289	958	1324	1221	1052

In the second year (Fig. 1), the autumn ploughing was slightly better than spring ploughing with skimmers or shallow tillage (treatment 4). The same *E. repens* level as in autumn ploughing was achieved with the KF-cultivator without (5) or with autumn ploughing (6). Trashboards or skimmers did not improve control efficacy against *E. repens*, which was surprising. The implements did typically bury stubble and weeds well, but in some cases *E. repens* rhizomes and shoots were left above the soil surface. Evidently, peat soil was very soft and therefore the buried pieces of *E. repens* grew very quickly through the furrows. On heavier soils the results could be more favourable for such implements.

Other weeds found were mainly annuals in both years, but their amounts were low (< 40 g DM m⁻²) and there were no statistically significant differences between the treatments.

The barley yields were 2500–3000 kg ha⁻¹ in the ploughed treatments (Fig. 2). Already in the first year the treatments without ploughing (4 & 5) produced significantly lower yields than spring ploughed treatments (1 & 2). In the second year all treatments with ploughing (1–3 & 6) produced significantly higher yield than treatments without ploughing (4 & 5). The reason for this could not be due only to a high infestation of *E. repens*, since in KF-treatment 5 the amount of *E. repens* was one of the lowest in the experiment (Fig. 1).

In all likelihood, the treatments without ploughing suffered at least in 2013 from the soil being too compacted. The yield difference in 2013 between treatments 5 and 6 may indicate this: treatment 6 had been ploughed in autumn 2012 and its barley yield was clearly better than in treatment 5, which was not ploughed. Otherwise, treatments 5 and 6 were conducted similarly in spring 2013. Ploughing in autumn or spring did not affect the barley yields (Fig. 2). Barley hectolitre weights were 60–63 kg hl⁻¹ and there were no significant differences between the treatments in either year.

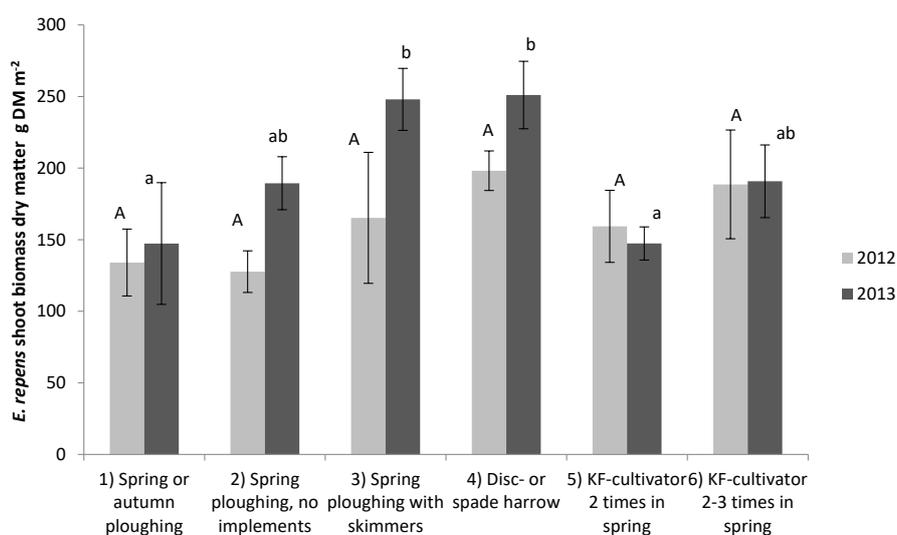


Fig. 1. Average dry matter of *E. repens* shoot biomass in autumn in experiment 1 (g DM m⁻²). The experiment was conducted in the same fixed place during 2012–2013. Standard deviations of the treatments are marked with bars (n = 4). The treatments with different letters were significantly different at 95% confidence. Note: The significance can be compared only within years, not between years.

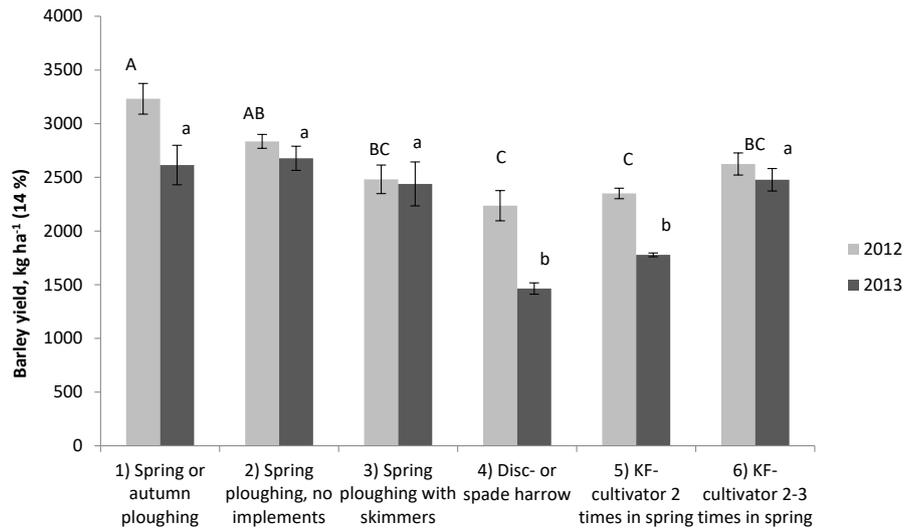


Fig. 2. Average barley yields (kg ha⁻¹) in experiment 1 (moisture content 14 %). The experiment was conducted in the same fixed place during 2012–2013. Standard deviations of the treatments are marked with bars (n = 4). The treatments with different letters were significantly different at 95% confidence. Note: The significance can be compared only within years, not between years.

Experiment 2

The treatment without bare fallow (1) had a substantial occurrence of *E. repens* before barley harvest (Fig. 3). The infestation of *E. repens* was even higher than in experiment 1, although all plots were ploughed in spring in experiment 2. Bare fallow with the KF-cultivator decreased *E. repens* dry weight 86–98% compared to treatment 1 (No bare fallow). The soil was soft, thus the beginning of tillage was easy with the KF-cultivator and the first pass with the rotary spade harrow seemed to be unnecessary. In the second year, an exceptionally high amount of *E. repens* was recorded in one sample in treatment 3. If this observation was assumed to be erroneous, the averages of treatments 2 and 3 would be very close to each other.

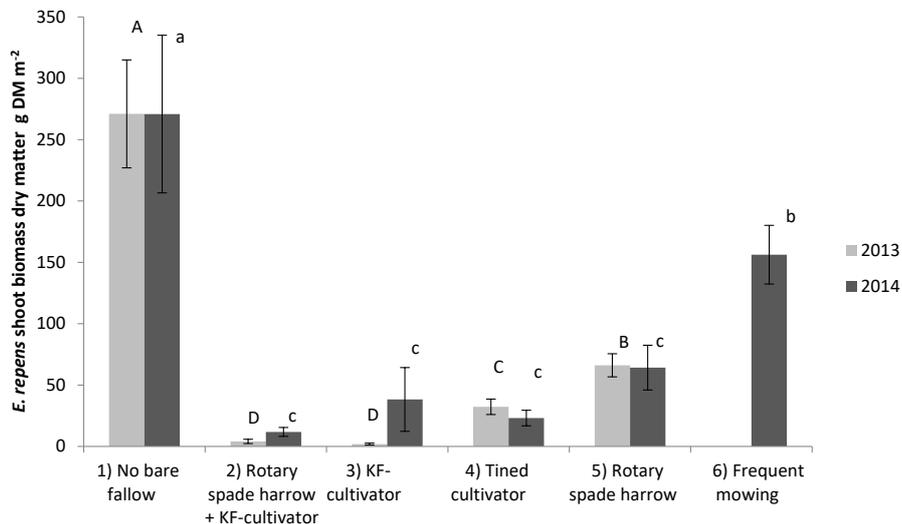


Fig. 3. Average dry matter of *E. repens* shoot biomass in autumn in experiment 2 (g DM m⁻²). The location of the experiment was changed between 2013 and 2014. Standard deviations of the treatments are marked with bars (n = 4). The treatments with different letters were significantly different at 95% confidence. Note: The significance can be compared only within of years, not between years.

Bare fallowing with a tined cultivator (4) decreased the amount of *E. repens* by 90% compared to the treatment without bare fallow (1), which is also a good result. The tined cultivator with narrow blades (2012) left the surface of the cultivated ley more even than the cultivator with goosefoot blades (2013). Rugged peat soil made driving uncomfortable during subsequent passes and consequently the working depth varied.

The rotary spade harrow (5) decreased the amount of *E. repens* by 75% compared to treatment 1 (Fig. 3). This is a satisfying result given that the harrow could not break the surface of the ley properly, although two passes were always made during the same day. This led to a high number of passes with 8–12 per summer. It is clear that the high amount of surviving *E. repens* (65 g DM m⁻²) will increase quickly during the coming years. In treatment 6, frequent mowing was not very effective against *E. repens* despite numerous passes. It was only able to destroy less than half of *E. repens* shoot biomass compared to the biomass growing in treatment 1. Despite a satisfactory mowing quality, the repeated mowing had a mediocre effect on *E. repens* shoot biomass.

Treatments 2–4 effectively decreased *E. repens*, but annual weeds occupied the free growing space. In both years there were about 30 g DM m⁻² of annual weeds in treatment 1. The amounts of annual weeds in treatments 2–4 ranged from 70–90 g DM m⁻² in 2013 and 115–145 g DM m⁻² in 2014. There were statistically significant differences between treatments 1 and 5 in 2013 and between treatments 1 and 3 & 4 in 2014. The annual weeds were mainly *Persicaria lapathifolia* and *Chenopodium album*. Especially in 2014, the amount of annual weeds was so high that barley was predisposed to lodging and the yields decreased due to competition. Weed harrowing at the shooting stage of barley would have been necessary, but a weed harrow was not available.

Barley yields were satisfying from an organic farming perspective, especially in 2013, which after using the KF-cultivator showed yields of about 3700 kg ha⁻¹ (Fig. 4). The treatment without bare fallow (1) produced a 1000 kg ha⁻¹ lower yield. In 2014, the emergence of annual weeds and crop lodging after thunder storms decreased barley yields. In treatments 2–5, barley yields were about 2500 kg ha⁻¹ and in treatment 1 again 1000 kg ha⁻¹ lower. After frequent mowing (6) barley yield was 2200 kg ha⁻¹. Barley hectolitre weights were 59–63 kg hl⁻¹ and there were no significant differences between the treatments in either year.

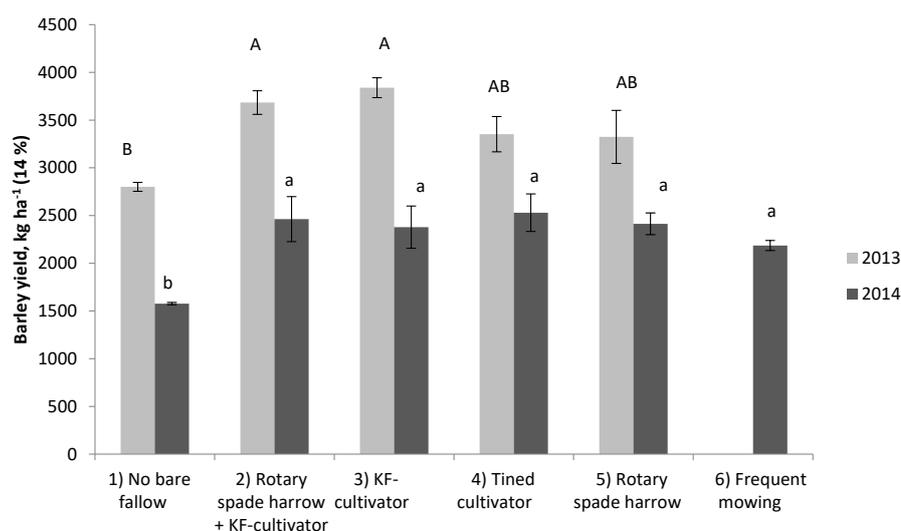


Fig. 4. Average barley yields (kg ha⁻¹) in experiment 2 (moisture content 14%). The location of the experiment was changed yearly. Standard deviations of the treatments are marked with bars (n = 4). The treatments with different letters were significantly different at 95% confidence. Note: The significance can be compared only within years, not between years.

Discussion

Experiment 1

A brief fallow in spring before cereal sowing was not sufficiently effective against *E. repens*. Peat soil is probably one of the most challenging soils from the point of view of mechanical weed control. Peat soil is moist and soft, thus the rhizomes and roots of perennial weeds are able to grow easily and rapidly.

After use of the KF-cultivator, the rhizomes of *E. repens* dried out and clearly turned brown, but obviously did not die completely. As the beginning of May in both years was rainy, it was only possible to start the cultivations quite late and therefore the fallowing time was only two weeks. This was clearly not a long enough period for an organic and moist soil. If there would have been stubble cultivation(s) already in previous autumn, the effect of spring treatments may have been improved, as seen in Jacobsson's (2006) experiments in Sweden.

If the situation is as in experiment 1 (high proliferation of *E. repens* in cereal stubble), better weed control results could probably be achieved by fallowing effectively from May through to the end of June. After that a green manure crop could be sown to suppress surviving weeds and to produce nitrogen for next year's crop (Thomsen et al. 2015).

Autumn ploughing was slightly better than spring ploughing, though not significantly. Unfortunately, autumn ploughing could be performed only in 2013 due to practical reasons. In agreement with our study, only a little difference in ploughing effects have been found in both light soils (Jacobsson 2006) and clay soils (Thomsen et al. 2015). As we only performed autumn ploughing in one year, our conclusions need to be tempered.

Thomsen et al. (2015) achieved good results against *E. repens* and *S. arvensis* already with three weeks of bare fallow in spring before green manure sowing (two-disc harrowing). The amount of *E. repens* in clay soil was less than 20 g DM m⁻² in the untreated control in the subsequent year, which was much less than in our experiment (about 140 g DM m⁻²). The initial weed situation and soil type were therefore more challenging in our study compared to Thomsen et al.'s (2015) study.

Ploughing in autumn or spring did not affect barley yields. Similar results were achieved in three years of conventional farming experiments in peat and sandy soils (Lötjönen & Isolahti 2010). Jacobsson (2006) likewise did not notice yield difference in light soils, but in heavier soils, spring ploughing produced a higher yield than autumn ploughing in one experimental year. However, spring ploughing can decrease seed germination in heavy soils if the weather is dry during spring. In our experiment, ploughing seemed to be necessary together with brief fallow to control *E. repens* and to improve cereal yield.

Experiment 2

The KF-cultivator very effectively reduced *E. repens* in experiment 2, even though the weather was rainy and cool in summer 2012. There were not many cultivation days that were dry enough and destruction of *E. repens* was probably more due to the exhaustion of rhizome food reserves than from drying out. There was one pass with the KF-cultivator in spring 2013 before ploughing, but not in spring 2014. This could explain why the effect of the KF-cultivator was not as good in 2014. Also ordinary cultivators had a beneficial effect, although after their use the field surface was left uneven, which made the following passes unpleasant, which can decrease the driving speed and thus working capacity.

In 2013, treatments were started about one month earlier than in 2012, which led to a higher number of passes. According to the results, it may not be sensible to increase the number of passes from the number carried out in 2012. Thus, four passes with the KF-cultivator in late summer and one the next spring seemed to be enough in these conditions taking into account the control efficacy and the costs. However, determining the optimum number of passes requires further research.

Midsummer fallows have been studied previously in both Denmark and Finland with significant but smaller reductions in *E. repens* than in our study. In these studies, fallow decreased the amount of *E. repens* by 50–75% compared to untreated control (Väisänen & Kakriainen-Rouhiainen 2004, Rasmussen et al. 2014). However, in our study the fallowing period was longer, since a catch crop/winter crop was not sown in autumn as in other studies.

The largest disadvantages in carrying out ley breakage by late summer fallow are likely to be from having bare and intensively tilled soil over the winter period, resulting in evident nutrient losses. Fallow during May–June could be a better option to break old leys. On the other hand, this kind of fallow should be compared to autumn ploughed ley in terms of nutrient losses and other disadvantages. The encouraging results seen with the KF-cultivator encourage further studies on other perennial weeds, e.g. *C. arvensis* and *S. arvensis*. Thus, further research is required before more detailed recommendations can be given to farmers.

Costs

The KF-cultivator has been criticized as being slow. The driving speed with the KF-cultivator can be 4–7 km h⁻¹, and thus the capacity of a 3.0 m machine could be 1.1–1.3 ha h⁻¹. The cost of one treatment would be about 60 EUR ha⁻¹. If we assume that 6 treatments are required when old ley is broken up, the method can be considered expensive. On the other hand, if ploughing and seedbed tillage can be excluded, the costs of 6 treatments would be about 180–230 EUR ha⁻¹. This is an acceptable cost for rigorous perennial weed control, since there is no need to repeat the treatment every year.

Depending on crop rotation and soil type, this kind of fallow may be necessary every fifth year or more rarely in organic farming. For example, if the crop rotation is two years of cereals plus three years of ley, it is probable that effectively managed late summer fallow during the last ley year will be enough for most situations.

Conclusion

In Finland, *E. repens* is the most harmful weed species causing considerable economic losses in crop production. Therefore, improved management practices are welcome to enhance the control of *E. repens*. Mechanical control methods are of interest not only for organic production but also for conventional cropping to meet the EU requirements of integrated weed management and sustainable use of herbicides. Including a bare fallow period in the crop rotation is a costly option which should end up with the most effective and long-lasting control of *E. repens*.

There were marked differences in control efficacy between the control strategies (timing) and different machinery studied in our field experiments. Evidently, to achieve an effective control of *E. repens*, the late summer and autumn period are more feasible than any quick efforts in the spring before sowing. Kwick-Finn weed cultivator proved to control *E. repens* very effectively and the economic return as yield increase in the subsequent barley crop was satisfactory.

The costs of rigorous mechanical weed control are reasonable if we assume that in well designed crop rotation this kind of operation may be needed every fifth year or rarely. In conclusion, effective control of *E. repens* is achieved with proper machinery and repeated treatments at the optimal time.

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Supplemental Figures



Suppl.Fig. 1. Kwick-Finn cultivator lifts the roots or rhizomes of perennial weeds to the soil surface so that sun and wind can desiccate them.



Suppl. Fig. 2. The working principle of Kwick-Finn cultivator: goosefoot tines loosen the soil and after that a PTO-driven rotor throws soil and weed roots into the air.



Suppl. Fig. 3. Skimmers installed on plough (between the mouldboards). This plough was used in experiment 1.



Suppl. Fig. 4. Trashboards installed on plough (above the mouldboards). This plough was used in experiment 1 and 2.



Suppl. Fig. 5. Disc harrow which was used in experiment 1 in the first year.



Suppl. Fig. 6. Rotary spade harrow which was used in experiment 1 in the second year and in experiment 2 in both years.



Suppl. Fig. 7. Tined cultivator with narrow blades was used in experiment 2 in the first year.



Suppl. Fig. 8. Tined cultivator with goosefoot blades was used in experiment 2 in the second year.



Suppl. Fig. 9. Horizontal rotary mower which was used in experiment 2 in the second year.