

# Control of *Elymus repens* by rhizome fragmentation and repeated mowing in a newly established white clover sward

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## Summary

Control of perennial weeds, such as *Elymus repens*, generally requires herbicides or intensive tillage. Alternative methods, such as mowing and competition from subsidiary crops, provide less efficient control. Fragmenting the rhizomes, with minimal soil disturbance and damage to the main crop, could potentially increase the efficacy and consistency of such control methods. This study's aim was to investigate whether fragmenting the rhizomes and mowing enhance the control of *E. repens* in a white clover sward. Six field experiments were conducted in 2012 and 2013 in Uppsala, Sweden, and Ås, Norway. The effect of cutting slits in the soil using a flat spade in a 10 × 10 cm or 20 × 20 cm grid and the effect of repeated mowing were investigated. Treatments were performed either during summer in a spring-sown white clover sward (three experiments) or during autumn, post-cereal harvest, in an under-sown white clover sward

(three experiments). When performed in autumn, rhizome fragmentation and mowing reduced *E. repens* shoot biomass, but not rhizome biomass or shoot number. In contrast, when performed in early summer, rhizome fragmentation also reduced the *E. repens* rhizome biomass by up to 60%, and repeated mowing reduced it by up to 95%. The combination of the two factors appeared to be additive. Seasonal differences in treatment effects may be due to rhizomes having fewer stored resources in spring than in early autumn. We conclude that rhizome fragmentation in a growing white clover sward could reduce the amount of *E. repens* rhizomes and that repeated mowing is an effective control method, but that great seasonal variation exists.

**Keywords:** *Agropyron repens*, *Elytrigia repens*, *Trifolium repens*, perennial weed, cutting, defoliation, mechanical weed control, cover crop, integrated weed management.

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## Introduction

*Elymus repens* (L.) Gould (couch grass) is a creeping perennial grass that causes significant yield losses in

both annual and perennial crops in the southern and northern temperate zone, including the Nordic countries. In conventional agriculture, control of *E. repens* is largely based on the use of herbicides containing

glyphosate, whereas organic farmers tend to rely on intensive tillage. However, both types of control have serious drawbacks. Although at trace levels most herbicides are considered as safe for human health, many herbicides and their derivatives can remain in food and feed crops and contaminate ground and surface water (Barceló, 1997; Hussain *et al.*, 2015). Glyphosate and its additives are considered comparatively safe (Duke & Powles, 2008), but can accumulate in the environment (Sviridov *et al.*, 2015) and their effects on the environment and human health are still under debate (Annett *et al.*, 2014). Moreover, overreliance on herbicides encourages the development and proliferation of herbicide-resistant weeds (Heap, 2014). Tillage, on the other hand, strongly increases the risk of nitrogen (N) leaching (Catt *et al.*, 2000) and soil erosion (Meyer *et al.*, 1999). Tillage to control *E. repens* carries an especially high risk of N leaching, as it is often performed in autumn. It is often repeated, without a subsequent crop that can take up N during winter, factors which tend to increase N leaching (Askegaard *et al.*, 2011; Aronsson *et al.*, 2015). Furthermore, CO<sub>2</sub> emissions due to fuel consumption and the energy input necessary for common tillage practices far exceed that of chemical control in conventional farming (Koga *et al.*, 2003; Tzilivakis *et al.*, 2005). Therefore, it is important to develop efficient *E. repens* control methods that have a lower environmental impact than intensive tillage or regular herbicide use.

Using subsidiary crops between cash crops to intensify and prolong the competitive pressure has been shown to have a suppressive effect on the general weed population (Teasdale *et al.*, 2007) and provide a number of other ecosystem services, such as N fixation, reducing N leaching, improving soil structure and increasing soil microbial activity and soil organic matter content (Lemessa & Wakjira, 2015). Given good establishment and growth, subsidiary crops under-sown into the main crop have been shown to compete well with *E. repens* during the autumn and substantially reduce the quantity of *E. repens* rhizome biomass compared with treatments without competition. However, even under very high competitive pressure, *E. repens* rhizome biomass has generally increased compared with the starting conditions (Cussans, 1972; Dyke & Barnard, 1976; Bergkvist *et al.*, 2010). The possibility of improving the effect of competition by mowing has been investigated, for example by Håkansson (1969) and Brandsæter *et al.* (2012). According to Håkansson (1969), regular defoliation does control *E. repens*, but a cutting interval of 14 days at soil level height is necessary to prevent new rhizomes developing. Brandsæter *et al.* (2012) and Ringselle *et al.* (2015) found a positive effect of mowing post-harvest, but it was inconsistent across years and relatively small compared with other control measures, such as tillage or

glyphosate spraying. Cussans (1973) found that even mowing as frequently as seven times per year in a ryegrass ley could not reduce the quantity of *E. repens* rhizomes below the starting value, but that it was more effective than three mowings per year.

Rhizome fragmentation is considered an important component of tillage for the control of *E. repens*. Buds on smaller rhizome fragments are more likely to activate and produce shoots than on larger rhizome fragments, but the division of resources between them means that shoots from smaller rhizome fragments are also relatively weaker (Vengris, 1962; Håkansson, 1968). As a consequence, mowing (Turner, 1966, 1968) and crop competition (Håkansson, 1971) may have a greater effect on shoots produced by smaller rhizomes fragments than shoots from larger ones. However, tillage is generally difficult to combine with growing crops without destroying them. Using a tillage implement with flat discs parallel to the direction of travel, we believe it is possible to fragment the rhizomes with minimal disturbance of the aboveground biomass, and by cutting the rhizomes in a cross-pattern, we expect them to be fragmented into small enough pieces to enhance the controlling effect of subsidiary crops and mowing. Our overall aim is to develop a strategy to control *E. repens* without using herbicides or destructive tillage and still benefit from services generated by a crop, for example a subsidiary crop or temporary grassland.

We tested the hypotheses that (i) fragmenting the rhizomes through cross-cutting slits in the soil increases the number of *E. repens* shoots post-cutting, that (ii) repeated mowing reduces the *E. repens* rhizome biomass, and that (iii) cross-cutting increases the efficacy of mowing on *E. repens* rhizome biomass. The hypotheses were tested during summer in a white clover (*Trifolium repens* L.) crop established in spring and post-harvest in a white clover crop that was under-sown in conjunction with the sowing of a spring cereal. In total, six field experiments were carried out in Norway and Sweden during 2012 and 2013. In the experiments, a spade was used to simulate cross-cutting, but a recently developed prototype, 'Kverneland Vertical rhizome/root cutter' (tractor propelled), can make similar slits at the field scale.

## Material and methods

### Locations and soils

Experiments were conducted in 2012 and 2013 at one location outside Uppsala, Sweden, and one outside Ås, Norway (Table 1). Fields were chosen that had established populations of *E. repens*, but were free, or almost free, of any other perennial weeds at the start of the

**Table 1** Co-ordinates, soil texture and climate information for the two sites used in the experiments (Uppsala and Ås), as well as management dates (sowing and harvest), treatment dates (cross-cutting and mowing) and sampling dates (pre-treatment, before 2nd mowing and post-treatment). Experimental protocol one and two are referred to as EP1 and EP2 respectively

	Uppsala				Ås	
Co-ordinates (WGS 84)	N 59°44' E 17°38'				N 59°40' E 10°46'	
Soil texture (0–20 cm)	20% clay, 43% silt, 32% sand, 4% soil organic matter				Sandy loam soil (USDA Soil Survey classification)	
Precipitation (1961–90)	527 mm				785 mm	
Temperature (1961–90)	5.5°C				5.3°C	
	EP1 - 2012	EP1 - 2013	EP2 - 2012	EP2 - 2013	EP1 - 2013	EP2 - 2012
Preceding crop	Spring wheat	Spring barley	Spring wheat	Spring barley	Spring barley	Spring barley
Crop	White clover	White clover	Barley White clover	Barley White clover	White clover	Oat White clover
Sowing	29-05-2012	22-05-2013	21 29-05-2012	17 22-05-2013	10-05-2012*	10 10-05-2012
Harvest	–	–	13-09-2012	15-08-2013	–	23-08-2012
Cross-cutting	27-06-2012	12-06-2013	21-09-2012	15-08-2013	30-07-2013	25-08-2012
Mowing	27-06-2012	12-06-2012	21-09-2012	15-08-2013	30-07-2013	25-08-2012
	16-07-2012	25-06-2012	08-10-2012	28-08-2013	14-08-2013	17-09-2012
	30-07-2012	01-07-2012	24-10-2012	04-09-2013	05-09-2013	
	09-08-2012	08-07-2012		11-09-2013	30-09-2013	
	21-08-2012	15-07-2012		19-09-2013		
	31-08-2012	23-07-2012		26-09-2013		
	11-09-2012			09-10-2013		
	20-09-2012	07-08-2012				
Pre-treatment shoot counting (I)	27-06-2012	11-06-2013	21-09-2012	15-08-2013	29-07-2013	25-08-2012
Shoot counting before 2nd mowing (II)	16-07-2012	25-06-2013	08-10-2012	28-08-2013	–	–
Post-treatment biomass sampling and shoot counting (III)	10-09-2012	19-08-2013	12-11-2012	29-10-2013	06-01-2014*	10-12-2012

\*Note that the white clover in Ås EP1 was sown the year before the treatment year and post-treatment sampling was performed in early January instead of in autumn as was done in Uppsala.

experiments. The fields on both locations were managed using organic practices (certified by KRAV in Sweden and without certification in Norway), including soil cultivation against perennial weeds. The farm outside Uppsala is managed by the Swedish University of Agricultural Sciences and the farm outside Ås by the Norwegian Institute of Bioeconomy Research. The experimental sites were mouldboard ploughed to about 25 cm depth in the autumn and harrowed the following spring, before sowing the crops that were used in the experiment. Co-ordinates, soil texture and climate information pertaining to the sites can be found in Table 1.

#### Experimental design, treatments and management

Two experimental protocols were used, each in three of six two-factorial field experiments, all arranged in complete randomised blocks with four replicates. In experimental protocol 1 (EP1), the treatments were performed in a pure stand of white clover (*Trifolium repens* L. cv. Milkanova; 10 kg ha<sup>-1</sup>) established in

**Table 2** Treatments used in the six field experiments investigating the effect of repeated mowing and/or cutting 10-cm-deep slits in the soil (cross-cutting grid) with a spade

Treatment	Belowground weed control		Mowing
	Cross-cutting	Distance between slits	
Control	No	–	No
C20	Yes	20 cm	No
C10	Yes	10 cm	No
M	No	–	Yes
MC20	Yes	20 cm	Yes
MC10	Yes	10 cm	Yes

the same spring at Uppsala and the previous spring at Ås (Table 1). In EP2, the treatments were performed after the harvest of a spring cereal (180 kg ha<sup>-1</sup> barley in Sweden and 200 kg ha<sup>-1</sup> oat in Norway) under-sown with white clover (10 kg ha<sup>-1</sup>). Experiments according to both protocols were performed in 2012 and 2013 in Uppsala, while in Ås EP1 was performed only in 2013 and EP2 only in 2012 (Table 1).

The two experimental factors were mowing and cross-cutting (Table 2). Mowing was performed repeatedly during both summer and early autumn in EP1, but only post-cereal harvest in EP2. Plots were mowed to 2–3 cm above soil surface in Norway using a cylinder lawn mower and 3–5 cm in Sweden using a rotary lawn mower. After the initial treatment, mowing was repeated when *E. repens* reached two to three leaves. However, in Uppsala 2012 (U2012), mowing reduced the amount of *E. repens* rhizomes to such low levels in EP1 that it affected the possibility to study the effect of fragmentation, while there was no significant effect of mowing in EP2. Therefore, the mowing frequency was reduced in U2013 EP1 and increased in U2013 EP2. This resulted in the plots being mowed eight and seven times during 2012 and 2013, respectively, in Uppsala EP1 and three and seven times in EP2; the EP1 experiment at Ås was mowed four times and EP2 mowed once (Table 1). Cross-cutting was performed immediately after the initial mowing in both EP. The slits were made 10 cm deep with a flat spade in a 20 × 20 cm or 10 × 10 cm grid according to treatment (Table 2). In EP1 U2013, additional plots of the control and C10 treatments were established to determine whether cross-cutting changed the distribution of rhizome fragment lengths. The treated plot size was 100 × 100 cm in Uppsala and 120 × 120 cm in Ås. A regularly mowed buffer zone was maintained outside the treated plots to minimise the risk of rhizome ingress in the plots.

### Sampling

Three measures were used to estimate *E. repens* abundance: shoot number, shoot biomass and rhizome biomass. All measurements and samples were taken in the 80 × 80 cm centre of the plots to limit edge effects and converted to densities m<sup>-2</sup> for graphs and tables, to ease comparisons.

*Elymus repens* shoot number was estimated by counting all living shoots (including tillers) at three occasions: (i) pre-treatment, (ii) before second mowing

in Uppsala and (iii) at final sampling (see Table 1 for dates). Shoot and rhizome biomass of *E. repens* were also collected (iii) at final sampling by cutting all aboveground biomass and digging up all the rhizome biomass down to 20 cm depth. Dry weight was ascertained by drying the samples at 105°C for 24 h in Uppsala and at 60°C for 120 h in Ås.

In Uppsala, a soil moisture sensor (ThetaProbe type ML2x, Delta-T Devices, UK) was used at the time of each mowing, taking 10 samples block<sup>-1</sup> (Fig. 1).

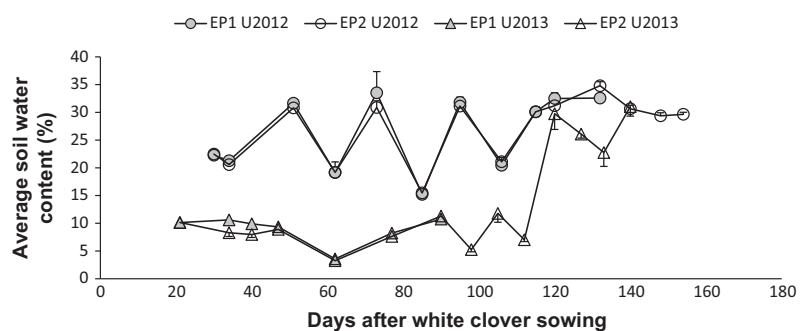
### Statistical analysis

Initially, a single model including both experimental protocols (EPs) was used, but due to many and highly significant interactions between EP and the other factors, it was decided to analyse the EPs separately. Thus, the data were analysed using an ANOVA linear mixed model consisting of the main effects (environment, cross-cutting, mowing) and their interactions as fixed variables and block as a random variable (Environment × block) (Table 3). The number of *E. repens* shoots pre-treatment was used as a covariate to adjust for field variation. The variables were transformed whenever appropriate to achieve approximate homoscedasticity (Table 3). Least square means and the confidence interval were then retransformed for graphical presentation of the results. Tukey's HSD tests or contrasts were used for mean comparisons. All analyses, transformations and retransformations were performed in JMP 10.0.0 (SAS Institute Inc.).

## Results

Cross-cutting in a 10 × 10 grid (C10) reduced the number of 15–20 cm rhizomes to about a fourth compared with the control (only sampled in EP1 U2013; Fig. 2;  $P = 0.003$ ) and increased the number of <10 cm rhizomes (contrast;  $P = 0.019$ ). C10 also resulted in a lower average rhizome weight than the control, 34 vs. 44 g dry weight m<sup>-2</sup> ( $P = 0.044$ ; data not shown).

**Fig. 1** Average soil water content (10 samples block<sup>-1</sup>) measured in connection with each mowing and sampling in Uppsala for experimental protocol 1 (EP1) and EP2. Note that soil water content was measured in EP2 in connection with mowing both EP1 and EP2. For exact mowing and sampling dates, see Table 1. Error bars are standard deviation.



### Experimental protocol 1 (EP1) – treatments in summer/early autumn

In EP1, there were fewer shoots in the cross-cut plots than in control, both before the second mowing (Time 2, Table 3; Fig. 3A) and at the final sampling (Time 3, Table 3; Fig. 3B). Moreover, at the final sampling, the rhizome biomass was up to 60% lower (Fig. 3C) and the shoot biomass up to 50% lower (3D) in the cross-cutting plots than in the control; the reduction was particularly noteworthy in the C10 treatments.

The first mowing did not affect the number of shoots that had emerged before the second mowing was performed (Table 3; data not shown). By the final sampling, however, mowing had reduced the number of shoots by up to 80% (Fig. 3B), rhizome biomass by up to 95% (Fig. 3C) and shoot biomass by up to 99% (Fig. 3D) compared with the control. The significant interaction between mowing and cross-cutting for rhizome and shoot biomass (Table 3; Fig. 3C) was

because the cross-cutting caused a larger reduction in the unmown plots than the mowed plots.

### Experimental protocol 2 (EP2) – treatments in autumn

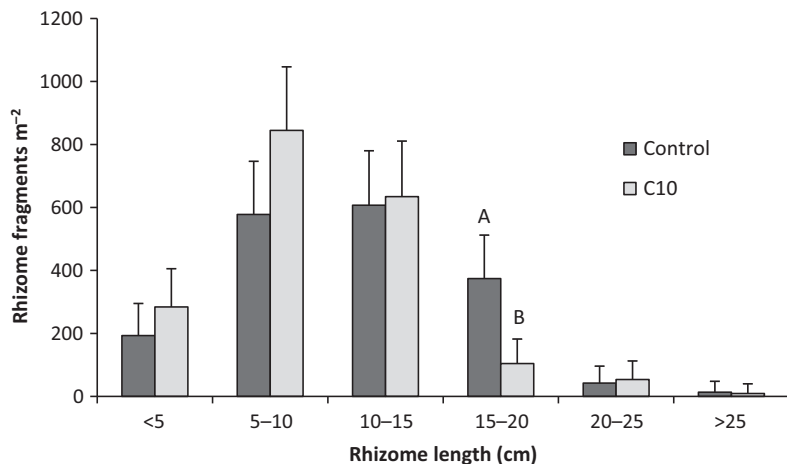
The shoot biomass was reduced by up to 85% by cross-cutting and mowing in EP2 (Table 3), but there were no effects on shoot numbers (Fig. 4A,B) or rhizome biomass (Fig. 4C). The shoot biomass was generally reduced by both measures, but there were significant interactions with environment (Table 3). The effect of both cross-cutting and mowing was clear in U2012, but the effect of cross-cutting was not clear in U2013 or at Ås (Fig. 4D).

## Discussion

The experiments showed no support for the hypothesis that fragmenting *E. repens* rhizomes through cross-

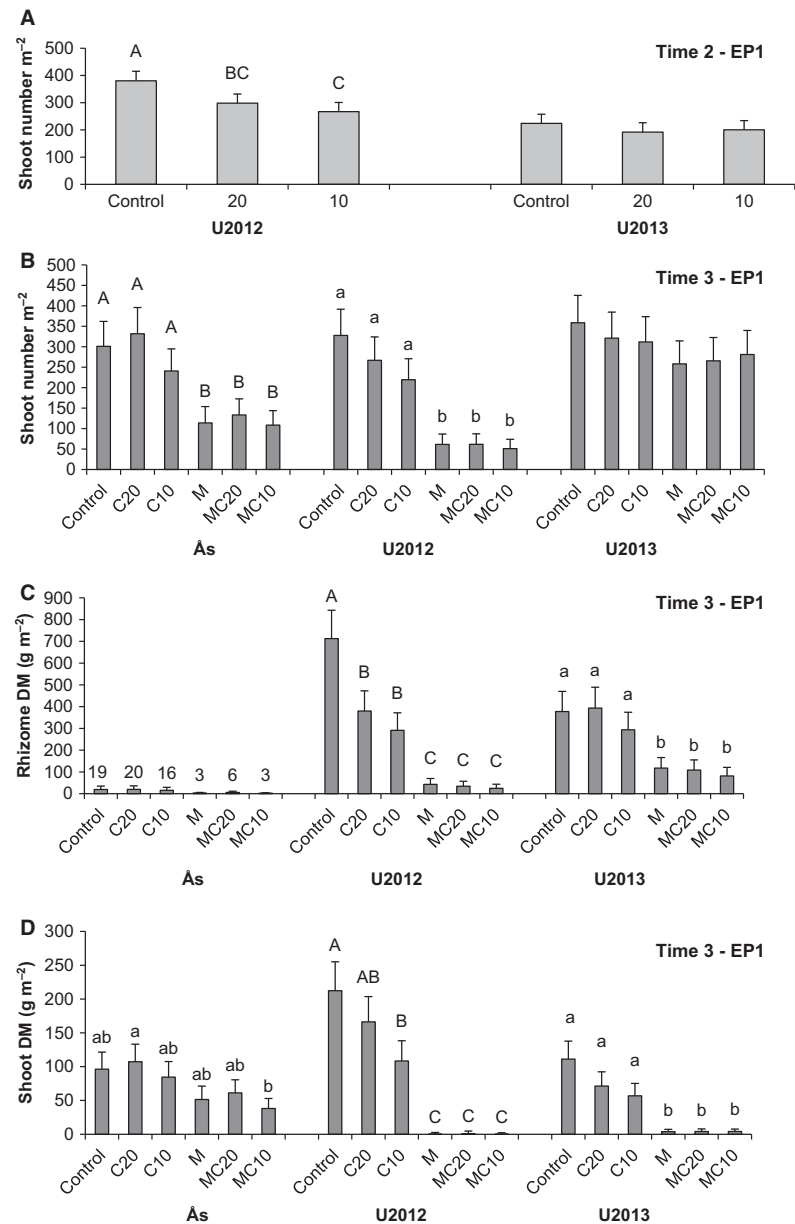
**Table 3** Analysis of variance table (ANOVA) of the statistical model used to calculate statistical significance for rhizome dry matter (DM), shoot DM and shoot number before 2nd mowing (Time 2) and post-treatment (Time 3) for experimental protocol 1 (EP1) and EP2. Shoot number pre-treatment (Time 1) was used as a covariate. The random variable block is not shown. Bold text indicates a *P*-value <0.05

	DF	EP1 (P)				EP2 (P)			
		Rhizome DM	Shoot DM	Shoot # Time 2	Shoot # Time 3	Rhizome DM	Shoot DM	Shoot # Time 2	Shoot # Time 3
Environment	2	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.6	<b>&lt;0.001</b>	<b>&lt;0.001</b>
Cross-cutting (CC)	2	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.028</b>	0.4	<b>0.001</b>	0.4	0.11
Environment × CC	4	<b>0.004</b>	0.3	<b>0.018</b>	0.2	0.8	<b>&lt;0.001</b>	0.5	0.4
Mowing (M)	1	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.12	<b>&lt;0.001</b>	0.3	<b>&lt;0.001</b>	0.7	0.075
Environment × M	2	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.4	<b>&lt;0.001</b>	0.7	<b>0.004</b>	0.9	<b>0.031</b>
CC × M	2	<b>0.048</b>	<b>0.019</b>	0.6	0.076	0.8	<b>&lt;0.001</b>	0.078	0.5
Environment × CC × M	4	<b>0.027</b>	0.2	0.4	0.9	0.10	<b>0.006</b>	0.5	0.4
Shoot # Time 1	1	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.021</b>	0.2	<b>&lt;0.001</b>	<b>&lt;0.001</b>
Transformation		Sqrt	Sqrt	None	Sqrt	Sqrt	Sqrt	None	Sqrt



**Fig. 2** Number of rhizome fragments of different lengths in the control and cross-cutting 10 × 10 cm treatment (C10) in experimental protocol 1, Uppsala 2013 (EP1 U2013). Error bars indicate 95% confidence intervals. Letters show the results of a Tukey HSD test at  $\alpha = 0.05$ .



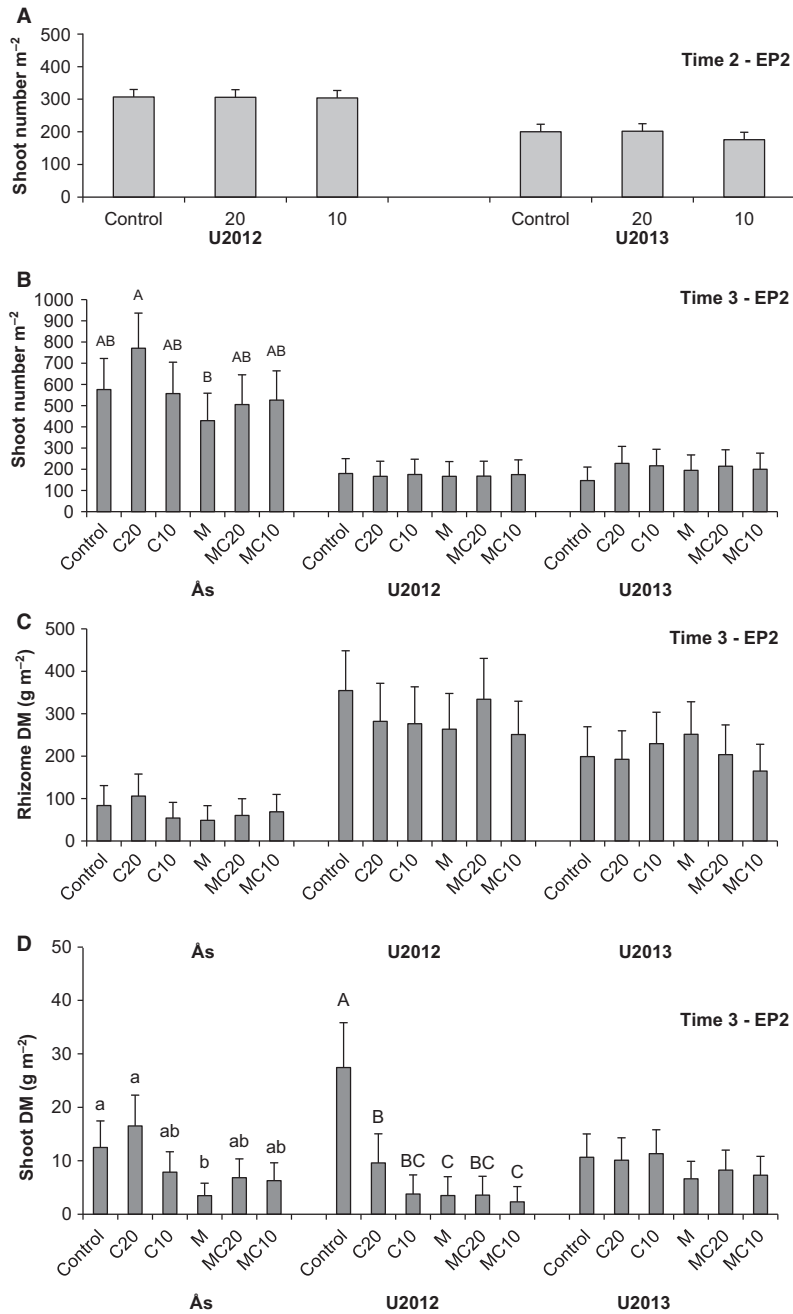


**Fig. 3** Effects of cross-cutting  $10 \times 10$  cm (C10) or  $20 \times 20$  (C20) and/or in combination with mowing (M) using experimental protocol 1 (EP1), that is treatments are performed in a white clover crop during summer and early autumn. Graphs are divided into three environments: Ås, Uppsala 2012 (U2012) and U2013. (A) Treatment effects on shoot number before the second mowing, (B) shoot number post-treatment, (C) rhizome dry matter (DM) post-treatment and (D) shoot dry matter post-treatment. Error bars indicate 95% confidence intervals. Letters show the results of a Tukey HSD test at  $\alpha = 0.05$ , divided by environment.

cutting increases the number of emerging *E. repens* shoots. Instead, the number of *E. repens* shoots was unaffected or reduced by cross-cutting. This may be because smaller rhizomes do not only have a higher bud activation tendency than larger rhizomes, but also potentially have a lower viability. For example, factors such as low N availability (Turner, 1966) and greater soil depth (Vengris, 1962; Håkansson, 1968) affect smaller rhizome fragments more negatively than larger rhizomes. Consequently, even if cross-cutting resulted in more buds being activated, the shoots produced may not survive to reach the surface and/or interspecific competition to the same extent as the control. The increased number of independent rhizome fragments may also have increased intraspecific competition.

Proctor (1972) found that a high density of 10 cm *E. repens* rhizomes had lower shoot survival and produced less rhizome biomass per cm rhizome than at a lower density.

Whether cross-cutting resulted in no change or a reduction in *E. repens* shoot numbers, rhizome biomass was influenced by the timing of the cross-cutting (EP1 or EP2) and its grid size (C10 or C20). The difference in control effect due to timing is likely because, in spring, the rhizomes were weaker following depletion of resources during winter, compared with rhizomes that had accumulated resources throughout summer (Håkansson, 1967). The more prominent and consistent reduction in *E. repens* shoot numbers and rhizome biomass by C10 compared with C20 could be



**Fig. 4** Effects of cross-cutting 10 × 10 cm (C10) or 20 × 20 (C20) and/or in combination with mowing (M) using experimental protocol 2 (EP2), that is treatments are performed in an under-sown white clover crop post-cereal harvest in autumn. Graphs are divided into three environments: Ås, Uppsala 2012 (U2012) and U2013. (A) Treatment effects on shoot number before the second mowing, (B) shoot number post-treatment, (C) rhizome dry matter (DM) post-treatment, and (D) shoot dry matter post-treatment. Error bars indicate 95% confidence intervals. Letters show the results of a Tukey HSD test at  $\alpha = 0.05$ , divided by environment.

explained by the fact that rhizomes had a much higher chance to be left intact or less damaged in the coarser grid than in the finer grid.

The significant reductive effect of cross-cutting on *E. repens* shoot numbers and rhizome biomass raises the question whether it can be used as a control measure in its own right. It is clear from the experiments, especially U2012 EP1, that cross-cutting can result in a reasonable reduction in *E. repens* rhizome biomass by the end of the growth period, compared with no cross-cutting. During spring–summer, the efficiency can most likely be enhanced by optimising the frequency, grid size and timing of the treatments. Studies on the effect

of cross-cutting on the companion crops are also necessary, to determine whether it has a greater negative effect on *E. repens* than on the companion crops. In autumn, however, the lack of effect means that it is unlikely to be an effective post-harvest control method even with optimisation, unless it can be enhanced by other efforts to control *E. repens*. In an experiment conducted in the same field and year as U2012, Ring-selle *et al.* (2016) found that tine cultivation post-harvest followed by ploughing resulted in a 50–70% reduction in rhizome biomass in the subsequent year, compared with ploughing alone. As the reductive effect of post-harvest tine cultivation on *E. repens* rhizome

biomass is greatly increased by mouldboard ploughing, burying the rhizomes (Cussans & Ayres, 1977), ploughing is likely to also enhance the effect of cross-cutting. However, as tine cultivation can have effects other than rhizome fragmentation (e.g. killing the shoot biomass, displacing the rhizomes, destroying the root system, pulling the rhizomes aboveground), it is likely that another mechanism than fragmentation contributes to the effect on *E. repens* in the post-harvest period.

There was clear support for the hypothesis that repeated mowing reduces *E. repens* rhizome biomass, but only when mowing was performed during summer (EP1), not in autumn (EP2). Thus, like *Cirsium arvense* (Bourdôt *et al.*, 2016), the efficacy of mowing on *E. repens* is greatly dependent on timing. These results are in line with previous studies that have found a limited and inconsistent effect of mowing on *E. repens* in the post-harvest period under Scandinavian conditions (Brandsæter *et al.*, 2012; Ringselle *et al.*, 2015). In contrast, other studies have found, on the same latitudes, a considerable build-up of rhizome biomass in undisturbed plants in August–September (Håkansson, 1967; Tørresen *et al.*, 2010; Boström *et al.*, 2013). This discrepancy indicates that either the autumnal rhizome accumulation varies greatly between years and environmental conditions, or mowing is generally not effective enough to disrupt it. Mowing may not be as effective during autumn, as it reduces light competition among plants and light is a scarcer resource during autumn than summer.

The effective reduction in *E. repens* rhizome biomass by repeated mowing during summer may be of interest to farmers. Farmers are unlikely to want to sacrifice a whole season for *E. repens* control. However, frequent mowing in a subsidiary crop, or short-term ley, may be more appealing than more extreme control methods, such as summer fallows (Karbozova-Saljniov *et al.*, 2004). The mowed subsidiary crop would still provide other services and prevent soil erosion (Lemessa & Wakjira, 2015). Of course, the high mowing frequency used in this study is not realistic for farmers. White clover generally benefits more from a high mowing frequency than grasses (Burdon, 1983) and is usually grown in mixture with grasses. A high mowing frequency would therefore likely reduce the competitive pressure on *E. repens* from the companion crops and reduce their other beneficial effects and the potential harvest value. Thus, there is a need to optimise the mowing frequency, height and timing to control *E. repens* as efficiently as possible.

An unexplored aspect in this study is what effect mowing and/or fragmenting the rhizomes through cross-cutting may have on the winter survival of the

rhizomes and shoots and their ability to compete in the following year. Perennial plants lose a significant portion of their stored carbohydrates in winter (Verwijst *et al.*, 2013), which may affect rhizome fragments of different sizes differently. The starving effect of mowing on the carbohydrate storage of rhizomes (Turner, 1968) may also result in a lower survival rate during winter and lower competitiveness in spring.

The experiments show support for the hypothesis that fragmenting the rhizomes through cross-cutting increases the efficacy of repeated mowing on *E. repens* rhizome biomass. However, while the hypothesised result was achieved, it was not caused by the predicted mechanism. As discussed above, rhizome fragmentation reduced rather than increased the number of *E. repens* shoots in EP1 and had no effect in EP2. Thus, there was no clear interaction between mowing and cross-cutting in EP2, and in EP1, the negative effect of cross-cutting was added on top of the negative effect of mowing. However, the negative effect of mowing was so strong in EP1 that the added effect of cross-cutting was small in absolute numbers. This means that a more realistic mowing frequency (about 2–4 times in grass–clover crops) may have resulted in a stronger interaction between mowing and cross-cutting. How cross-cutting and mowing affects *E. repens* and subsidiary crops requires further investigation.

## Conclusions

- Rhizome fragmentation through cross-cutting does not increase the number of *E. repens* shoots. However, the directly reductive effect of cross-cutting on *E. repens* rhizome biomass, when performed in the summer, makes it an interesting control method to explore.
- Repeated mowing reduces *E. repens* rhizome biomass, when performed in summer.
- Combining cross-cutting with mowing has the potential to be an effective control method for *E. repens*. Further studies need to optimise the timing and frequency of the control methods, as well as to determine the potential effects of cross-cutting on the subsidiary crop.

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