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

G BERGKVIST*, B RINGSELLE*, E MAGNUSKI*, K MANGERUD† & L O BRANDSÆTER†‡

*Department of Crop Production Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden, †The Division of Biotechnology and Plant Health, Norwegian Institute of Bioeconomy Research (NIBIO), As, Norway, and ‡Department of Plant Sciences, Faculty of Biosciences, Norwegian University of Life Sciences, As, Norway

Received 15 December 2016
Revised version accepted 27 January 2017
Subject Editor: Adam Davis, USDA-ARS, USA

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 As, 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.

BERGKVIST G, RINGSELE B, MAGNUSKI E, MANGERUD K & BRANDSÆTER LO (2017). Control of *Elymus repens* by rhizome fragmentation and repeated mowing in a newly established white clover sward. *Weed Research* 57, 172–181.

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; Aromsson et al., 2015). Furthermore, CO₂ 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 rye-grass 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 As, 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 |

| Preceding crop | EP1 - 2012 | EP1 - 2013 | EP2 - 2012 | EP2 - 2013 | EP1 - 2013 | EP2 - 2012 |
|---------------|------------|------------|------------|------------|------------|------------|
| Crop          | Spring wheat | Spring barley | Spring wheat | Spring barley | Spring barley | Spring barley |
| 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 | 27-06-2012  | 11-06-2013  | 21-09-2012   | 15-08-2013   | 29-07-2013  | 25-08-2012  |
| counting (I)   |            |            |            |            |            |            |
| Shoot counting | 16-07-2012  | 25-06-2013  | 08-10-2012   | 28-08-2013   | –           | –           |
| before 2nd mowing (II) |            |            |            |            |            |            |
| Post-treatment | 10-09-2012  | 19-08-2013  | 12-11-2012   | 29-10-2013   | 06-01-2014* | 10-12-2012  |
| biomass       |            |            |            |            |            |            |
| sampling and shoot |            |            |            |            |            |            |
| counting (III) |            |            |            |            |            |            |

*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.

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 |
|-----------|--------------------------|
|           | Cross-cutting | Distance between slits | Mowing |
| 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 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\(^{-1}\)) established in 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\(^{-1}\) barley in Sweden and 200 kg ha\(^{-1}\) oat in Norway) undersown with white clover (10 kg ha\(^{-1}\)). 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 As 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 As. 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⁻² 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 As.

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⁻¹ (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⁻² (\( P = 0.044 \); data not shown).

![Fig. 1](image-url) Average soil water content (10 samples block⁻¹) 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.

© 2017 The Authors. Weed Research published by John Wiley & Sons Ltd on behalf of European Weed Research Society. 57, 172–181
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 As (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

|                     | EP1 (P) |                     |                     | EP2 (P) |                     |                     |
|---------------------|---------|---------------------|---------------------|---------|---------------------|---------------------|
|                     | DF      | Rhizome DM          | Shoot DM            | Shoot # | Shoot # Time 2      | Shoot # Time 3      |
| Environment         | 2       | <0.001              | <0.001              | <0.001  | <0.001              | <0.001              |
| Cross-cutting (CC)  | 2       | <0.001              | <0.001              | <0.001  | 0.028               | 0.4                 |
| Environment × CC    | 4       | 0.004               | 0.3                 | 0.018   | 0.2                 | 0.8                 |
| Mowing (M)          | 1       | <0.001              | <0.001              | 0.12    | <0.001              | 0.3                 |
| Environment × M     | 2       | <0.001              | <0.001              | 0.4     | <0.001              | 0.7                 |
| CC × M              | 2       | 0.048               | 0.019               | 0.6     | 0.076               | 0.8                 |
| Environment × CC × M| 4       | 0.027               | 0.2                 | 0.4     | 0.9                 | 0.10                |
| Shoot # Time 1      | 1       | <0.001              | <0.001              | <0.001  | <0.001              | 0.021               |
| Transformation      | Sqrt    | Sqrt                | None                | Sqrt    | Sqrt                | Sqrt                |
|                      |         |                     |                     |         |                     |                     |
|                      |         | Transformation      |                     |         |                     |                     |

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 α = 0.05.
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. 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
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, Ringselle 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...
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 (Bourdöt 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 (Brandsetter 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-Saljnikov 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.

Acknowledgements

The work was funded by EU-FP7 as part of OSCAR (Optimizing Subsidiary Crop Applications in Rotations).

References

Annett R, Habibi HR & Honkela A (2014) Impact of glyphosate and glyphosate-based herbicides on the
freshwater environment. *Journal of Applied Toxicology* **34**, 458–479.

**Aronsson H, Ringselle B, Andersson L & Bergkvist G** (2015) Combining mechanical control of couch grass (*Elymus repens* L.) with reduced tillage in early autumn and cover crops to decrease nitrogen and phosphorus leaching. *Nutrient Cycling in Agroecosystems* **102**, 383–396.

**Askegaard M, Oleen JE, Rasmussen IA & Kristensen K** (2011) Nitrate leaching from organic arable crop rotations is mostly determined by autumn field management. *Agriculture, Ecosystems & Environment* **142**, 149–160.

**Barceló D** (1997) *Trace Determination of Pesticides and their Degradation Products in Water*. Elsevier, Amsterdam, the Netherlands.

**Bergkvist G, Adler A, Hansson M & Weih M** (2010) Red fescue undersown in winter wheat suppresses *Elytrigia repens*. *Weed Research* **50**, 447–455.

**Boström U, Andersson L, Forkman J, Hakman I, Liew J & Magnuski E** (2013) Seasonal variation in sprouting capacity from intact rhizome systems of three perennial weeds. *Weed Research* **53**, 387–398.

**Bourdot GW, Basse B & Criggs MG** (2016) Mowing strategies for controlling *Cirsium arvense* in a permanent pasture in New Zealand compared using a matrix model. *Ecology and Evolution* **6**, 2968–2977.

**Brandsæter LO, Goul Thomsen M, Waernhus K & Fykse H** (2012) Effects of repeated clover undersowing in spring cereals and stubble treatments in autumn on *Elymus repens*, *Sonchus arvensis* and *Cirsium arvense*. *Crop Protection* **32**, 104–110.

**Burdon JJ** (1983) *Trifolium repens*. *Journal of Ecology* **71**, 307–330.

**Catt J, Howse K, Christian D, Lane P, Harris G & Goss M** (2000) Assessment of tillage strategies to decrease nitrate leaching in the Brimstone Farm Experiment, Oxfordshire, UK. *Soil and Tillage Research* **53**, 185–200.

**Cussans GW** (1972) A study of the growth of *Agropyron repens* (L.) Beauv. during and after the growth of spring barley as influenced by the presence of undersown crops. In: *Proceedings of the 11th British Weed Control Conference*, 689–697, Brighton, UK.

**Cussans G** (1973) A study of the growth of *Agropyron repens* (L.) Beauv. in a ryegrass ley. *Weed Research* **13**, 283–291.

**Cussans G & Ayres P** (1977) An experiment on cultural and chemical control of *Agropyron repens* in 5 successive years of spring barley. In: *Proceedings of the EWRS Symposium on the Different Methods of Weed Control and Their Integration*, 171–179, Uppsala, Sweden.

**Duke SO & Powles SB** (2008) Glyphosate: a once-in-a-century herbicide. *Pest Management Science* **64**, 319–325.

**Dyke GV & Barnard AJ** (1976) Suppression of couch grass by Italian ryegrass and broad red clover undersown in barley and field beans. *The Journal of Agricultural Science* **87**, 123.

**Hakansson S** (1967) Experiments with *Agropyron repens* (L.) Beauv. III. Production of aerial and underground shoots after planting rhizome pieces of different lengths at varying depths. *Annals of the Agricultural College of Sweden* **34**, 31–51.

**Hakansson S** (1969) Experiments with *Agropyron repens* (L.) Beauv. IV. Response to burial and defoliation repeated with different intervals. *Annals of the Agricultural College of Sweden* **35**, 61–78.

**Hakansson S** (1971) Experiments with *Agropyron repens* (L.) Beauv. X. Individual and combined effects of division and burial of the rhizomes and competition from a crop. *Swedish Journal of Agricultural Research* **1**, 239–246.

**Heap I** (2014) Herbicide resistant weeds. In: *Integrated Pest Management*, (D Pimentel & R Peshin), 281–301. Springer, Springer Netherlands.

**Hussain S, Arshad M, Springael D et al.** (2015) Abiotic and biotic processes governing the fate of phenylurea herbicides in soils: a review. *Critical Reviews in Environmental Science and Technology* **45**, 1947–1998.

**Kar佐佐瓦·萨尔尼科夫 E, Funakawa S, Akhmetov K & Kosaki T** (2004) Soil organic matter status of Chernozem soil in North Kazakhstan: effects of summer fallow. *Soil Biology & Biochemistry* **36**, 1373–1381.

**Koga N, Tsuruta H, Tsui H & Nakano H** (2003) Fuel consumption-derived CO2 emissions under conventional and reduced tillage cropping systems in northern Japan. *Agriculture, Ecosystems & Environment* **99**, 213–219.

**Lemessa F & Wakahira M** (2015) Cover crops as a means of ecological weed management in agroecosystems. *Journal of Crop Science and Biotechnology* **18**, 123–135.

**Meyer L, Darney S, Murphree C, Harmon W & Grissinger E** (1999) Crop production systems to control erosion and reduce runoff from upland silty soils. *Transactions of the ASAE* **42**, 1645.

**Proctor D** (1972) Intercompetition between *Agropyron repens* and peas. *Weed Research* **12**, 107–111.

**Ringselle B, Bergkvist G, Aronsson H & Andersson L** (2015) Under-sown cover crops and post-harvest mowing as measures to control *Elymus repens*. *Weed Research* **55**, 309–319.

**Ringselle B, Bergkvist G, Aronsson H & Andersson L** (2016) Importance of timing and repetition of stubble cultivation for post-harvest control of *Elymus repens*. *Weed Research* **56**, 41–49.

**Sviridov A, Shushkova T, Ermakova I, Ivanova E, Epiketov D & Leontievsky A** (2015) Microbial degradation of glyphosate herbicides (Review). *Applied Biochemistry and Microbiology* **51**, 188–195.

**Teasdale JR, Brandsæter LO, Calegari A & Skora Neto F** (2007) Cover crops and weed management. In: *Non-chemical Weed Management* (eds MK Upadihya & RE Blackshaw ), 49–64. CAB International, Vancouver, BC.

**Torresen K, Fykse H & Rafoss T** (2010) Autumn growth of *Elytrigia repens*, *Cirsium arvense* and *Sonchus arvensis* at high latitudes in an outdoor pot experiment. *Weed Research* **50**, 353–363.
TURNER DJ (1966) A study of the effects of rhizome length, soil nitrogen and shoot removal on the growth of *Agropyron repens* (L.) Beauv. In: Proceedings of the 8th British Weed Control Conference, 538–545, Brighton, UK.

TURNER DJ (1968) *Agropyron repens* (L.) Beauv—some effects of rhizome fragmentation, rhizome burial and defoliation. *Weed Research* 8, 298–308.

TZILIVAKIS J, JAGGARD K, LEWIS KA, MAY M & WARNER DJ (2005) Environmental impact and economic assessment for UK sugar beet production systems. *Agriculture, Ecosystems & Environment* 107, 341–358.

VENGRIS J (1962) The effect of rhizome length and depth of planting on the mechanical and chemical control of quackgrass. *Weeds* 10, 71–74.

VERWIJST T, ECKERSTEN H, ANBARI S, LUNDKVIST A & TORSSELL B (2013) Weight loss in overwintering below-ground parts of *Sonchus arvensis* under current and temperature-elevated climate scenarios in Sweden. *Weed Research* 53, 21–29.