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Vertical rhizome disking to reduce *Elymus repens* (quackgrass) abundance in grass-clover leys

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ABSTRACT

Elymus repens is a problematic perennial weed in annual crops, grasslands and leys. Rhizome fragmentation by vertical disking can potentially reduce *E. repens* abundance with minimal tillage, but data are lacking on its efficiency in forage production. In a two-year study (2017–2018, 2018–2019) conducted in two forage grass-clover leys that were mostly weed-free except for large *E. repens* populations, this study examined effects on forage yield, botanical composition, and *E. repens* rhizome biomass of rhizome fragmentation at significant growth initiation in spring (early rhizome fragmentation, ERF) and/or when conditions allowed after the first forage cut (late rhizome fragmentation, LRF). Cold, wet springs and hard, dry soil in summer delayed treatment in both treatment years, to late spring (ERF) and late summer/early autumn (LRF). In the treatment year, ERF reduced first-cut forage yield by 44% compared with no rhizome fragmentation, while LRF decreased second- and third-cut yield by 24% and 53%, respectively. In the year after treatment, ERF increased total forage yield by on average 10%, while LRF had no effect. Over both years, combined forage yield was reduced by 11% by ERF and 4% by LRF. Both treatments reduced *E. repens* rhizome biomass, but inconsistently (ERF by 25% in one year only, LRF by 24% at one of two sites). ERF reduced *E. repens* incidence in forage by 10% in the treatment year, but had no effect in the following year. Thus, rhizome fragmentation by vertical disking can reduce *E. repens* abundance in grass-clover leys, but the effect is inconsistent and forage yield can be impaired, especially in swards with much *E. repens*. Moreover, disking is hampered by hard, dry soil conditions.

1. Introduction

Creeping perennial plants pose a great challenge in integrated pest management (IPM), conservation agriculture, and especially organic farming (Melander et al., 2016). In conventional agriculture, perennial weeds are usually controlled with non-selective herbicides (most commonly glyphosate) in the intercrop period or with selective herbicides in the growing crop (e.g. herbicides that primarily target grass weeds). Intensive tillage is generally required to control creeping perennials in the absence of herbicides (DiTommaso and Prostak, 2021). However, intensive tillage is time- and energy-demanding and can lead to long periods of bare soil, posing a high risk of nutrient leaching (Myrbeck et al., 2012) and soil erosion (Klik and Rosner, 2020). There is therefore a need for alternative control methods and management strategies for perennial weeds, particularly in reduced tillage, no-till, and organic systems.

Elymus repens (L.) Gould (quackgrass) is a perennial rhizomatous grass that can cause severe yield losses in both annual and perennial crops (Ringselle et al., 2020). In areas such as northern Europe where cereals and leys are the major crops, *E. repens* is particularly difficult to control, as there are few effective selective herbicides targeting *E. repens* in these crops. Therefore, glyphosate and tillage are often applied in the intercrop period to control *E. repens* (Lötjönen and Salonen, 2016).

The seeds of *E. repens* are only viable for a few years and do not have any inherent means of travel (Werner and Rioux, 1977). Instead, the main propagative capacity of *E. repens* and its high competitiveness

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derive from its rapidly expanding rhizome network. The rhizomes function as propagation, storage, and exploration organs (Kleijn and Van Groenendael, 1999), while clonal integration enables sharing of resources and information between clonal plants/ramets (Liu et al., 2016).

A common non-chemical control strategy is repeated non-inversion tillage (e.g., using a disk cultivator/harrow) to fragment the rhizome network and starve *E. repens* by forcing it to use its resources to re-shoot multiple times, followed by inversion ploughing in late autumn or spring (Brandsæter et al., 2017). The smaller the rhizome fragments and the deeper they are buried in the soil, the less likely new shoots are to reach the soil surface (Håkansson, 2003), while rhizome fragments placed on or very close to the soil surface can be desiccated. A similar effect of rhizome/root fragmentation and burial has been reported for many other perennial weeds with shallow underground storage organs. These include the tropical invasive weed *Cyperus aromaticus* (L.) (Navua sedge) (Chadha et al., 2022), the rhizomatous shrub *Calligonum arborescens* (L.) Litv. (Luo and Zhao, 2015), and the vine *Calystegia sepium* (L.) R.Br. (hedge bindweed) (Rask and Andreasen, 2007).

Rhizome fragmentation without burial has long been believed to cause *E. repens* to propagate, making it create more numerous but less vigorous shoots (Håkansson, 1968). However, recent studies have found that rhizome fragmentation often results in either an increase in the number of main shoots at the expense of tillers (Kolberg et al., 2018) or a direct reduction in shoot numbers and rhizome production (Bergkvist et al., 2017; Ringselle et al., 2018). Bergkvist et al. (2017) found that fragmentation by shovel down to 10 cm depth in a 10 cm × 10 cm pattern reduced *E. repens* rhizome production in a white clover (*Trifolium repens* L.) crop by up to 60%. Ringselle et al. (2018) tested a tractor-drawn prototype with vertical coulter disks developed by the Kverneland Group and found promising results, with the implement reducing *E. repens* rhizome biomass by 38% when used once prior to sowing of Italian ryegrass (*Lolium multiflorum* Lam.) and red clover (*Trifolium pratense* L.), and 63% when performed twice, prior to sowing and after the first cut. Apart from being detrimental to *E. repens*, this treatment was beneficial for the yield of the mixed grass-clover crop, both when it was performed before and after sowing of the crop. In fact, the beneficial effect on Italian ryegrass was actually higher when it was performed in the growing crop (170% vs 78%) (Ringselle et al. (2018). However, both those studies only investigated treatment effects in the year in which the grass-clover crop was established and only estimated yield in autumn of the treatment year.

Perennial weeds such as *E. repens* tend to increase in abundance as grasslands and leys age (DiTommaso and Prostak, 2021), replacing higher-yielding and more nutritious sown species and posing an infestation risk to subsequent crops. Rhizome fragmentation may not be fully efficient in managing *E. repens* as a single measure (Ringselle et al., 2018), but it might be more efficient when combined with a competitive ley crop and regular forage cuts, especially if rhizome fragmentation can be performed with optimal timing in the growing crop. *Elymus repens* is less sensitive to cutting than some other perennial weeds such as *C. arvense* and *Sonchus arvensis* (L.) (field sow-thistle) (Thomsen et al., 2015), but is more sensitive than e.g., *R. obtusifolius* (van Evert et al., 2020). After harvest of the main crop, under-sown cover crops with or without repeated cutting have a marginal effect on *E. repens* biomass in most cases, especially in regions with a short autumn growing season (Brandsæter et al., 2012; Melander et al., 2013; Ringselle et al., 2015; Lötjönen and Salonen, 2016; Salonen and Ketoja, 2020). However, there are some exceptions, e.g., Bergkvist et al. (2010) found that red fescue (*Festuca rubra* L.) under-sown with winter wheat (*Triticum aestivum*) reduced *E. repens* rhizome biomass by 40%. With forage cuts every two weeks during summer, high efficacy of control (>75%) can be achieved (Bergkvist et al., 2017; Ringselle et al., 2018). A more reasonable cutting frequency has sometimes been found to be sufficient to manage *E. repens* (e.g., Štýbnarová et al., 2013), but cutting is usually not sufficient on its own (Ringselle et al., 2020), potentially owing to clonal differences in *E. repens* as regards susceptibility to cutting (Neuteboom, 1981).

The aim of this study was to provide proof of concept that rhizome fragmentation in grass-clover leys, cut according to local practice, can increase the proportion of the sown crops and reduce the proportion of *E. repens*. Specific objectives were to quantify the effect of rhizome fragmentation on the competitive relationships between *E. repens* and sown grasses and clovers, and determine the effect on harvestable yield. The hypotheses tested were that vertical disking can (1) reduce *E. repens* abundance in grass-clover leys, measured as rhizome biomass in autumn, and the fraction of *E. repens* shoot biomass in the forage, and (2) increase forage yield.

2. Materials and methods

2.1. Site descriptions

Field experiments were conducted in two grass-clover forage leys near Uppsala, central Sweden, that were mostly weed-free except for large natural populations of *E. repens*. One ley, at Lövsta (59°50′N, 17°46′E), had been managed grassland prior to the experiments and the soil at the site consisted of 50% clay, 46% silt, and 4% sand, with an organic matter content of 5% of total soil mass. According to the ammonium acetate lactate extraction (AL) method (Egnér et al., 1960), available P and K content at the start of the study was 21 mg kg^{-1} and 205 mg kg^{-1} soil, respectively. The other ley was a grass-clover crop at Säby (59°49′N, 17°42′ E) that was under-sown in spring barley in 2015. The soil at that site consisted of 21% clay, 50% silt, and 29% sand, the organic matter content was 5% of total soil mass, and available P and K content was 25 mg kg^{-1} and 93 mg kg^{-1}, respectively.

2.2. Experimental design

The same experimental design was used at both sites (Lövsta and Säby), in two experimental periods (EP1: 2017–2018, EP2: 2018–2019), giving a total of four experiments (Lövsta EP1, Lövsta EP2, Säby EP1, Säby EP2). The experimental design consisted of two factors, each with two levels. Factor 1 was early rhizome fragmentation (ERF) conducted in spring when soil was sufficiently dry and before major growth started (levels: performed or not performed). Factor 2 was late rhizome fragmentation (LRF) conducted as soon as conditions allowed after the first cut (levels: performed or not performed). Each experiment had complete blocks with five replicates. Plots were 4 m × 12 m, but only the 1.5 m × 12 m strip along the center axis was used for sampling and yield determination.

2.3. Management and treatment details

Management, sampling, and treatment dates are shown in Table 1. The grass-clover mixture was under-sown in barley in 2015 at Säby and re-sown in conjunction with the treatments at Lövsta (2017 in EP1, 2018 in EP2). A seed mixture suitable for southern and central Sweden was used at both sites, consisting of 47% timothy (*Phleum pratense* L.) cv. Switch, 18% meadow fescue (*Festuca pratensis* L.) cv. Tored, 18% perennial ryegrass (*Lolium perenne* L.) cv. SW Birger, 10% red clover cv. Vicky and 7% white clover cv. Edith. Seeding was performed with a Nordsen Lift-o-matic 3 m seeder. No fertilizer was used at Säby, but at Lövsta 20 ton ha^{-1} cattle liquid manure were applied early in spring in all experimental years and equally in all experimental plots. Three cuts were performed each year, according to local practice, using a forage plot harvester (Haldrup F-55, Haldrup GmbH) with a cutting height of approximately 8 cm.

Rhizome fragmentation was performed with a prototype machine developed by the Kverneland Group that uses disk coulters taken from a plow to make vertical slits in the soil, thus fragmenting e.g., rhizomes with minimal disturbance to the soil. Fragmenting the rhizomes without disturbing the soil is intended to damage the rhizomes of *E. repens* more than the roots of forage crops, thus shifting the sward away from

Table 1
Management, sampling, and treatment dates in experiments in experimental periods EP1 (2017–2018) and EP2 (2018–2019) at the Säby and Lövsta sites. Early (ERF) and late (LRF) rhizome fragmentation and rhizome sampling were only performed in the first year of the experiment (Y1).

		EP1				EP2			
		Säby		Lövsta		Säby		Lövsta	
		Y1	Y2	Y1	Y2	Y1	Y2	Y1	Y2
Rhizome fragmentation	ERF	24-Apr	–	4-May	–	8-May	–	8-May	–
	LRF	26-Jun	–	26-Jun	–	28-Aug[a]	–	28-Aug[a]	–
Cuts	1st	15-Jun	13-Jun	20-Jun	13-Jun	13-Jun	[c]	13-Jun	[c]
	2nd	08-Aug	27-Aug	08-Aug	27-Aug	27-Aug	01-Aug	27-Aug	31-Aug
	3rd	20-Oct	11-Oct	18-Oct	[b]	11-Oct	14-Sep	12-Oct	19-Oct
Rhizome sampling		24-Oct	–	26-Oct	–	01-Nov	–	01-Nov	–

[a] Conditions were not suitable for rhizome fragmentation until late August, due to extreme summer temperatures.
[b] Insufficient biomass for a third cut.
[c] Harvesting performed, but yield not recorded.

E. repens towards more productive forage crop species. The prototype machine was similar to that used by Ringselle et al. (2018), but with wipers added close to the disks to prevent soil from being lifted by the rotating disks. The plan was to use the same treatment strategy as in Ringselle et al. (2018), i.e., making two runs with the machine (the second run perpendicular to the first) to create a crisscross pattern, with 10 cm treatment depth and 10 cm disk spacing.

Both 2017 and 2018 were challenging years for vertical disking treatments due to adverse weather conditions (cold, wet spring and cold, dry summer in 2017; dry and exceptionally hot summer in 2018) (for temperature and precipitation data, see Supplementary Table S1). Thus, the ERF and LRF treatments could not be applied in early spring and early summer as originally intended (see treatment dates in Table 1) and disking depth varied between 5 and 11 cm (see Supplementary Table S2). Even with extra weights added (up to one ton), it was difficult to perform the LRF treatment in dry summer conditions, especially in the heavy clay soil at Lövsta. In 2017, the machine was tilted when performing LRF at Lövsta to put extra weight on the front row of disks so that they could penetrate the soil, and was run twice in each direction to achieve a disk spacing of 10 cm in a crisscross pattern.

2.4. Sampling

To obtain a pre-treatment value of *E. repens* abundance, *E. repens* shoot density was measured just before ERF, using a grading fork (Ringselle et al., 2015). The grading fork gives an ordinal value of between 0 and 3 for shoot density, by registering occurrence/non-occurrence of at least one *E. repens* shoot in the three inter-tine areas (3×0.333 m^2) of the fork. The fork was placed 10 times at regular intervals along the middle of each plot.

Rhizome biomass of *E. repens* was collected in autumn of the treatment year (Y1; 2017 in EP1 and 2018 in EP2) by digging up all rhizomes within two 0.25 m^2 quadrants (dates in Table 1). Dead rhizomes were separated from living rhizomes before drying, and the living rhizome fraction was dried at 60 °C for 72 h for determination of dry matter content.

The plan was to record forage yield for all three cuts in Y1 and in the following year (Y2; 2018 in EP1 and 2019 in EP2), in 1.5 m × 12 m strips per plot. However, the third cut in Y2 of Lövsta EP1 was not performed, since dry conditions made the harvested yield essentially zero, while yield of the first cut in Y2 of both Lövsta and Säby EP2 was not recorded due to an error.

Samples for analysis of botanical composition were taken immediately before the first two cuts in each year, by taking 12 fist-sized vegetation samples in the central strip of each plot and pooling them to one sample per plot. Each sample was then separated into six fractions: *E. repens*, sown grasses, red clover, white clover, annual weeds, and other perennial weeds. All fractions were dried at 60 °C for 72 h and weighed to determine dry matter composition and dry matter content for yield calculations. Because the first cut in Y2 of EP2 was not recorded, it was decided to determine the botanical composition of the second and third cut instead. However, for Lövsta EP2 the botanical composition could only be analyzed in the third cut, since poor vigor of plants in the second cut hampered species identification.

Soil water content was measured using a soil moisture sensor (ThetaProbe type ML2x, Delta-T Devices, England) (for results, see Table S1). The nitrogen (N) content of *E. repens* shoots was determined using samples taken before the second cut in Y1. The concentration of total N and total carbon (C) in the sampled shoots was determined by dry combustion according to ISO 13878 (1998) and ISO 10694, respectively, using an elemental analyzer for macro samples (Trumac CN, Leco Corp, St. Joseph, MI, USA).

2.5. Statistical analysis

Before analysis, forage yield and rhizome biomass were converted to g m^{-2} and total (cumulative) yield was calculated for all cuts per year and combined for both years (Y1 + Y2). Due to some cuts not being recorded in Y2, the yield calculations for Y2 only included cuts 1 and 2 in EP1 and cuts 2 and 3 in EP2. Thus the yield data were only analyzed per cut in Y1, and not Y2. Due to a high level of heteroscedasticity, yield data were $\log_e$-transformed.

Rhizome biomass and total yield were analyzed using mixed linear models with the main factors (ERF, LRF, site, EP) and their interactions as fixed factors, and replicate as a random factor. Site and EP were analyzed as fixed factors to determine whether there were any significant interactions with the two treatments (ERF and LRF). However, as the interactions were generally weaker than the main factors, it was deemed unnecessary to analyze each site and EP separately. Since yield per cut and botanical composition were measured repeatedly over the years in the same plots, they were analyzed with the factor cut as a repeated measure. All statistical analyses were performed in Rstudio 1.2.5033 (RStudio, Inc.) using R 4.1.1 (R Foundation).

3. Results

3.1. Vegetation cover

There was no significant difference in *E. repens* pre-treatment density between the treatments (Supplementary Table S3). At the time of the first cut in Y1, *E. repens* dominated (>50%) the vegetation cover at all sites/years except Säby EP2 (Table 2). By the last botanical composition sampling of the experiments, the fraction of *E. repens* had decreased in all four experiments, even where no rhizome fragmentation had been performed (Table 2). At Lövsta, there were negligible amounts of sown grasses present in the sward in Y1, but significant amounts of white clover and weeds (Table 2). Sown grasses appeared in Y2 at Lövsta, making up a small proportion of the vegetation cover in EP1 but a considerable proportion in EP2 (Table 2).

Table 2
Botanical composition (%) of the sward in plots with no rhizome fragmentation at the first cut (C1), second cut (C2), and/or third cut (C3) in the treatment year (Y1) and the subsequent year (Y2) in experimental periods (EP) 2017–2018 and 2018–2019 at the Lövsta and Säby sites. Tukey tests showed significant differences over years and cuts.

	Lövsta							Säby							
	EP1				EP2			EP1				EP2			
	Y1		Y2		Y1		Y2	Y1		Y2		Y1		Y2	
	C1	C2	C1	C2	C1	C2	C3[a]	C1	C2	C1	C2	C1	C2	C2	C3[a]
Elymus repens (%)	89a	76a	76a	56b	59a	54a	11b	53a	9c	22b	8b	16a	8bc	12 ab	4c
Red clover (%)	1a	6a	3a	7a	16a	2a	22a	23b	46b	29 ab	37 ab	26b	38b	35b	72a
White clover (%)	6b	12 ab	11 ab	22a	9b	2b	2 ab	0	0	0	0	0	0	0	0
Sown grass (%)	0a	0a	6b	9b	0a	0a	32b	24b	45a	49a	55a	57a	54a	52a	23b
Other (%)	3a	6a	3a	5a	16a	6b	3b	0	0	0	0	0	0	0	0

[a] Data not available for C1, so C3 was sampled instead. For Lövsta EP2, there was insufficient plant biomass to make a botanical analysis for C2.

3.2. Rhizome biomass

Both ERF and LRF reduced *E. repens* rhizome biomass, but there were significant ERF:EP and LRF:Site interactions (Fig. 1, Table 3). ERF reduced rhizome biomass significantly in EP2 (by 25%), but not in EP1, while LRF reduced rhizome biomass significantly at Lövsta (by 24%), but not at Säby.

3.3. Forage yield

The ERF treatment and ERF:Site interaction had a significant effect on total forage yield in Y1 (Table 3). ERF reduced total forage yield in Y1, but the effect was more pronounced at Lövsta than at Säby (−32% vs. −19%) (Fig. 2). LRF had a significant effect on total forage yield in Y1 (Table 3), but seemingly mostly due to the effect of the ERF + LRF treatment. On its own, LRF only gave significantly different total forage yield from the control plots at Säby EP1 (−21%) (Fig. 2). Compared with no rhizome fragmentation, on average ERF reduced forage yield in the first cut by 44%, while LRF reduced yield in the second and third cuts in Y1 by 24% and 53%, respectively (Fig. 3).

In contrast to Y1, in Y2 ERF increased total forage yield by on average 10%, while LRF had no significant effect on total forage yield in Y2 (Fig. 2). Over the two years, ERF significantly reduced combined forage yield by 11%, while LRF reduced combined forage yield by 4%.

3.4. Biomass fractions

The main effect of ERF was significant for the *E. repens* fraction in Y1 (Table 3), with ERF resulting in a lower *E. repens* fraction than no-ERF (42.3 vs 46.7%). Analysis of the ERF:LRF:Site interaction indicated that ERF + LRF had a greater reducing effect on the *E. repens* fraction than only ERF, but only at the Lövsta site (Fig. 4). In Y2, there was no significant treatment effect on the *E. repens* fraction (Table 3). In Y1, ERF and LRF had no significant effect on the clover fraction (Table 3), but for the sown grass fraction there was a significant LRF effect and a significant ERF:LRF:EP interaction whereby LRF reduced the sown grass fraction at Säby compared with the control (35% vs. 46%) (Table 3, Fig. 4).

3.5. N content of *E. repens* shoots

There were no significant differences in total N content in *E. repens* shoots, but there was a trend ($P = 0.058$) for higher N content in *E. repens* shoots in the ERF treatments in Y1.

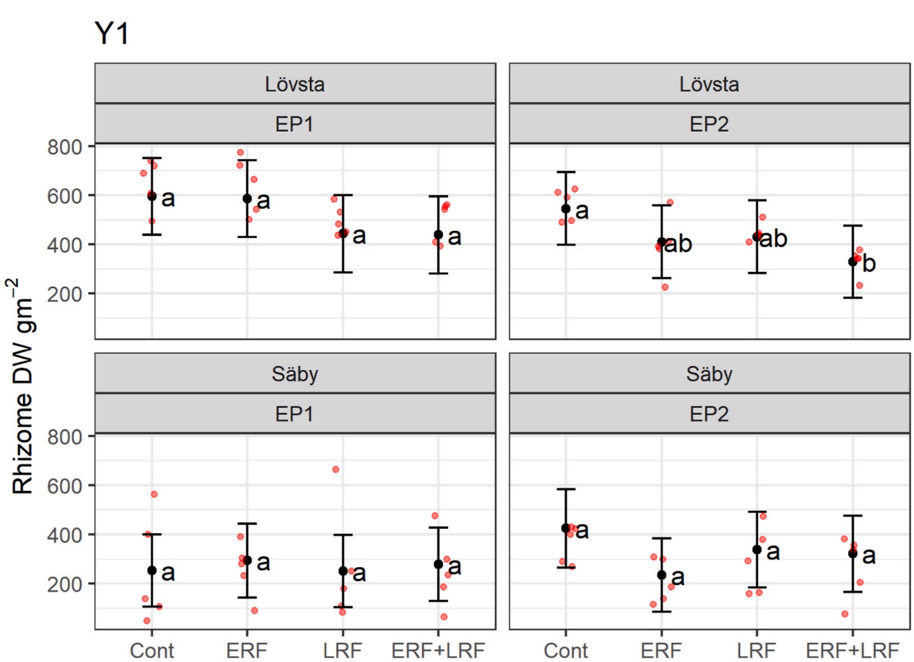

Fig. 1. Rhizome biomass in autumn of the treatment year (Y1) at the Säby and Lövsta sites during the two experimental periods (EP) 2017–2018 and 2018–2019. Red dots show the original data points for the five replicates. Black dots and error bars show the emmeans and 95% confidence interval, respectively. Letters show the result of Tukey HSD tests per site and EP.

Table 3
Chi-square values obtained in ANOVA for effects of early rhizome fragmentation (ERF), late rhizome fragmentation (LRF), experimental period (EP), site, and/or forage cut, and their interactions, on rhizome biomass, forage yield, and biomass fractions in the treatment year (Y1) and/or in the subsequent year (Y2). For clarity, interactions with cut that had no significant results are not shown. Values in bold are significant ($p \leq 0.05$), with asterisks indicating significance level (*p < 0.05, **p < 0.01, ***p < 0.001). *Elymus repens* shoot density was used as a covariate, df = 1 for all terms except cut (and its interactions) for yield Y1 per cut (df = 2).

	Rhizomes Y1	Total yield Y1	Total yield Y2	Total yield Y1+Y2	Yield Y1 - per cut	*E. repens* fraction Y1	*E. repens* fraction Y2	Clover fraction Y1	Sown grass fraction Säby Y1
Covariate	**8****	0	1	0	0	**10*****	0	2	**14*****
ERF	3′	**155*****	**12*****	**44*****	**35*****	**9****	0	1	0
LRF	**6***	**11*****	0	**5***	**160*****	0	0	3	**7****
EP	0	**9****	**410*****	**192*****	**98*****	**135*****	0	**45*****	**43*****
Site	**26*****	**821*****	**410*****	**1091*****	**1165*****	**499*****	**429*****	**80*****	
ERF:LRF	1	0	0	0	0	0	1	1	1
ERF:EP	**5***	4′	3	1	**7****	0	0	0	2
LRF:EP	0	0	3	1	**29*****	0	0	0	1
ERF:Site	0	**13*****	0	4′	2	1	0	0	
LRF:Site	**5***	5	1	1	1	1	1	2	
EP:Site	**8****	**81*****	**237*****	**9****	2	0	**222*****	**29*****	
ERF:LRF:EP	1	3	0	1	2	1	1	2	**4****
ERF:LRF:Site	0	0	0	0	0	**5***	0	**5***	
ERF:EP:Site	0	1	1	**5***	0	1	0	0	
LRF:EP:Site	0	0	1	0	1	0	1	3	
ERF:LRF:EP:Site	1	2	0	1	2	1	2	0	
Cut					**3530*****	**127*****	**141*****	**147*****	0
ERF:Cut					**114*****	1		1	0
LRF:Cut					**128*****	0		2	**4***
EP:Cut					**1695*****	**55*****		**5***	**25*****
Site:Cut					**168*****	**21*****		**11*****	
ERF:EP:Cut					**10****	0		1	3′
LRF:EP:Cut					**248*****	1		0	1
EP:Site:Cut					**178*****	**22*****		**8****	
LRF:EP:Site:Cut					**14*****	0		2	
ERF:LRF:Cut					2	3		1	**5***

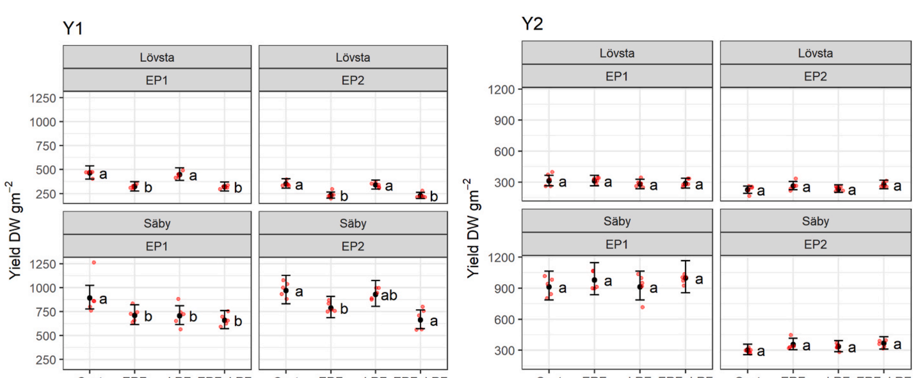

Fig. 2. Total forage yield of the three cuts in treatment year (Y1) at the Säby and Lövsta sites during the two experimental periods (EP) 2017–2018 and 2018–2019. In the subsequent year (Y2), only cuts 1 and 2 were taken in EP1, and cuts 2 and 3 in EP2. Red dots show the original data points for the five replicates. Black dots and error bars show the emmeans and 95% confidence interval, respectively. Letters show the result of Tukey HSD tests per site and EP.

4. Discussion

The hypothesis that vertical disking in grass-clover leys can reduce *E. repens* rhizome biomass and the proportion of *E. repens* in forage biomass was supported by the results obtained in this study. However, the effect observed was not as strong or as consistent as that reported by Ringselle et al. (2018) and Bergkvist et al. (2017), where up to 60% reduction in rhizome biomass was achieved. Several factors may have contributed to the lower efficacy in the present study. First, high clay content in the soil (Lövsta), compactness of the established grass-clover leys, and dry conditions during the study period all made it more difficult to reach the target treatment depth, even with more weight on the machine than in Ringselle et al. (2018). As a result, rhizomes located deeper in the soil profile may not have been fragmented to the same degree as in previous studies. Second, moist conditions in spring in combination with clayey soil probably also caused some compaction damage from the wheels at ERF, which may have been more detrimental to the crop than to *E. repens*. It is well-known that crops (e.g. Shaheb et al., 2021) and *E. repens* (Werner and Rioux, 1977) are negatively affected by soil compaction, but the fast-growing rhizomes of *E. repens* can likely exploit poor crop growth due to soil compaction (Steen and Håkansson (1987). Third, dry conditions during both summers delayed LRF, to August in EP2, since low soil moisture content made soil penetration difficult. This was not a problem in the study by Ringselle et al. (2018), where the forage crops were sown in the same year as the treatment was performed and the soil was thus softer. Findings by Bergkvist et al. (2017) indicate that rhizome fragmentation performed late in the season is far less effective in controlling *E. repens* than when performed in early summer. Similarly, Liew et al. (2013) found that due to dormancy, fragmentation in late summer-autumn was ineffective in

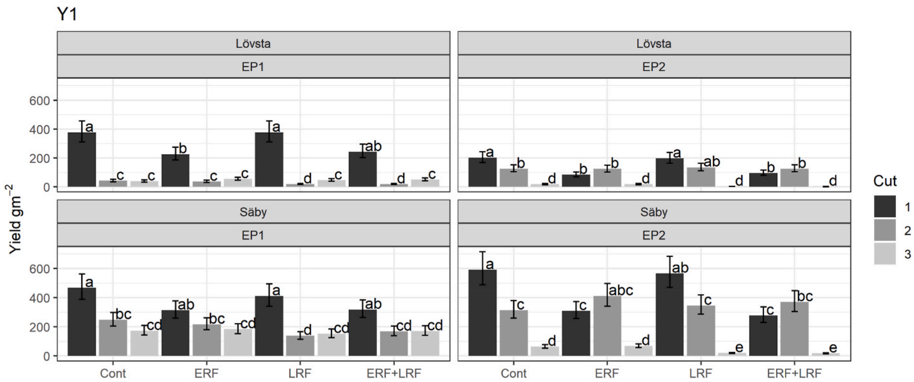

Fig. 3. Yield per cut in the treatment year (Y1) at the Säby and Lövsta sites during the two experimental periods (EP) 2017–2018 and 2018–2019. Bars show emmeans with 95% confidence intervals. Letters show the result of Tukey HSD tests per site and EP.

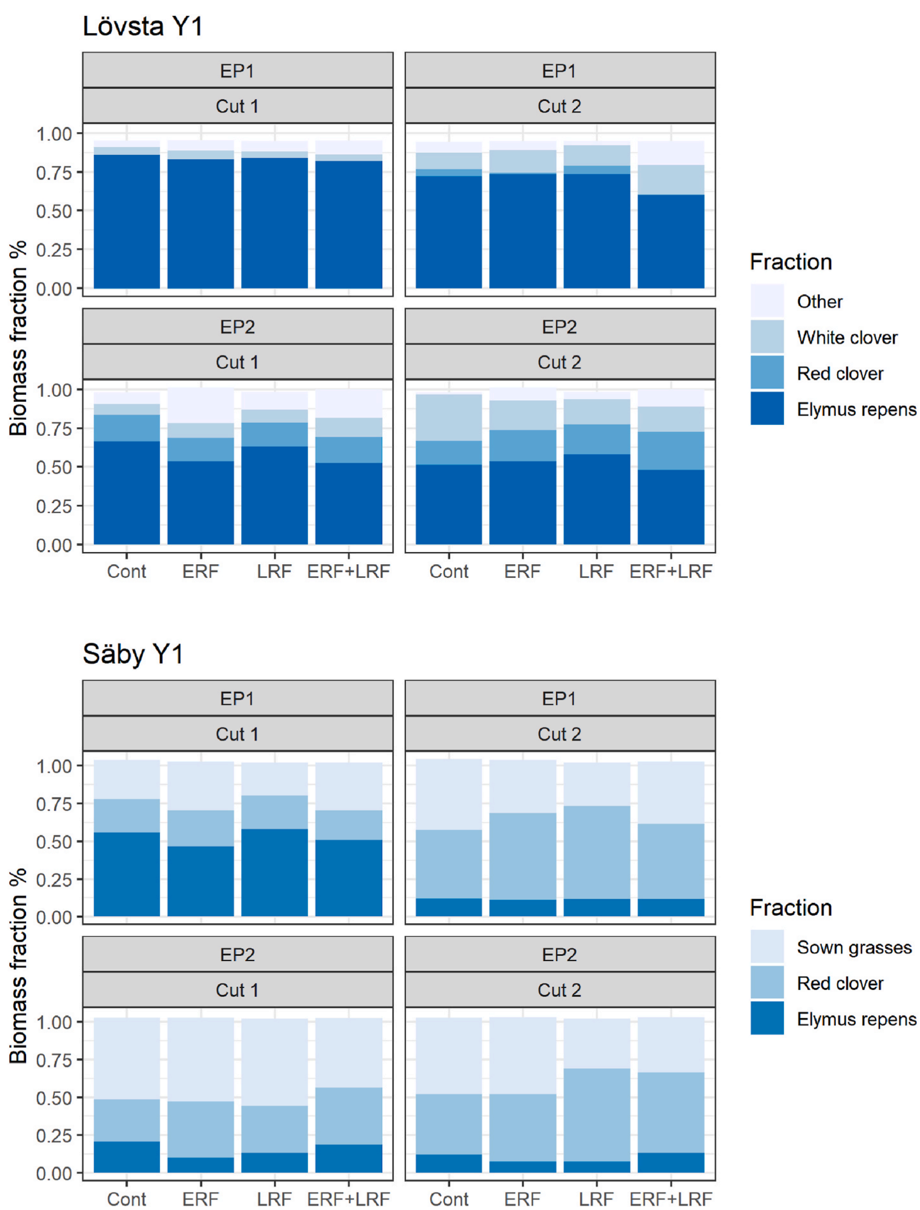

Fig. 4. Biomass fractions of *E. repens*, red clover, white clover, and other biomass in the first and second cut of the treatment year (Y1) at the Säby and Lövsta sites during the two experimental periods (EP) 2017–2018 and 2018–2019. There were no significant differences between treatments, only main effects (Table 3).

controlling *Equisetum arvense* (L.) (common horsetail), *S. arvensis*, *T. farfara*, and some populations of *E. repens*. Moreover, Bergkvist et al. (2017) found a less pronounced effect of *E. repens* rhizome fragmentation in the driest of their experimental years. The underlying mechanism was not investigated, but *E. repens* is a relatively drought-tolerant plant species (Janská et al., 2018) so it may have been less affected by drought than the sown grasses and clovers.

Farmers are generally advised not to fragment *E. repens* rhizomes without burying the fragments, especially in wet conditions, to avoid the risk of increased shoot emergence (Håkansson, 2003). While vertical disking did not reduce *E. repens* abundance as much as expected in the present study, it also did not increase *E. repens* abundance. This is further evidence that rhizome fragmentation primarily has a negative effect on *E. repens*, rather than increasing shoot production (similar to Bergkvist et al., 2017; Kolberg et al., 2018; Ringselle et al., 2018). However, other aspects of mechanical control (e.g., pulling the rhizomes through the soil) could still lead to spread of *E. repens* across the field. Fragmenting *E. repens* rhizomes in the absence of competition is most likely also ill-advised, as the weakened rhizomes could more easily recover (Anbari et al., 2016; Kolberg et al., 2018).

The hypothesis that vertical disking can increase forage yield was not supported by the data. Both ERF and LRF reduced yield of the cut that followed treatment and, while the yield stabilized at subsequent cuts in both treatments, it was not enough to compensate for the initial loss and total forage yield over the two years was still negative for ERF and LRF. Of course, treatment to reduce *E. repens* in grass swards consisting primarily of *E. repens* is likely to cause a yield reduction, since the weed itself comprises a large part of the harvested forage (Lunnan et al., 2018). It is possible that the positive effect on forage yield would continue in subsequent years if the proportion of sown species in the sward continued to increase. However, while the proportion of *E. repens* in harvested biomass decreased to some degree in Y1, the shift towards sown forage species was much smaller than observed by Ringselle et al. (2018) and did not persist into Y2.

The studies by Ringselle et al. (2018) and Bergkvist et al. (2017) indicated good potential of rhizome fragmentation to reduce *E. repens* abundance in growing crops. The present study confirmed its potential, but with the caveat that the current vertical disk implement has limited functionality in hard soil, even with added weight. However, other weed control measures commonly also have limitations regarding the weather and soil conditions in which they can be used. Moreover, summer conditions in the experimental years were exceptionally dry and the clay content in the experimental soils was higher than in many agricultural soils in Europe (European Soil Data Centre, 2023).

As found in previous studies (e.g. Liew et al., 2013), the results showed the importance of treatment timing and revealed trade-offs. For example, ERF lowered total forage yield since it reduced yield in the most important cut in the two-year study, i.e., the first cut after the treatment, while performing rhizome fragmentation in the summer (i.e., LRF) increased the risk of hard, dry soil conditions delaying or even preventing treatment. Thus, using vertical disking to control *E. repens* in grass-clover leys has potential, but the method most likely requires fine-tuning and a site- and year-specific treatment regimen in order to be effective. In fact, the method might be more suitable for use in annual crops sown in non-inversion tillage systems, where rhizomes can be expected to grow superficially and the soil is loosened by tillage, rather than in leys with generally compact soil.

Cutting regimen was not included as an experimental factor in this study, but it is interesting to note that the proportion of *E. repens* declined in all plots, regardless of treatment, particularly in EP1. In a review of non-chemical management of *E. repens*, Ringselle et al. (2020) found many reports that cutting *E. repens* can produce new rhizomes and increase the population size, even at very high cutting frequencies (e.g. Cussans, 1973; Neuteboom, 1981). The review also showed that high cutting frequencies can drastically reduce *E. repens* rhizome biomass (Bergkvist et al., 2017; Ringselle et al., 2018) and that even two-three cuts per year can sometimes keep *E. repens* under control (Pavlů et al., 2011; Štýbnarová et al., 2013). This discrepancy can partly be explained by some *E. repens* clones being more susceptible to cutting than others (Neuteboom, 1981). Cutting in summer can also give very different results than cutting in autumn (Liew et al., 2013; Bergkvist et al., 2017). However, there may be explanations other than effects of cutting, e.g., the sown species may successfully reduce the proportion of *E. repens* through competition or the *E. repens* population may decline for an unknown reason.

This study focused on *E. repens*, but there are many other perennial weeds and invasive species with relatively shallow underground storage organs (e.g., *S. arvense*, *C. aromaticus*, *Solidago canadensis* (L.) (Canada golderod)) and, in particular, grass weeds that are difficult to control by cutting (e.g., *Poa annua* (L.) (annual bluegrass), *Cynodon dactylon* (L.) Pers (Bermuda grass)) for which fragmentation could play a role in an IPM strategy (Weber, 2011; Carroll et al., 2021). Such IPM strategies can reduce the need for tillage and herbicides (Riemens et al., 2022). Many studies have examined the effects of separating ramet plants from their mother plant by rhizome/stolon fragmentation (Song et al., 2013) or burying rhizome fragments of different lengths (e.g. Luo and Zhao, 2015), but very few studies have performed these treatments under realistic conditions, e.g., fragmentation or burial in situ in agricultural soil without damaging the rest of the plant or its competitors.

5. Conclusions

Rhizome fragmentation by vertical disking reduces *E. repens* rhizome biomass and the proportion of *E. repens* shoots in grass-clover swards. However, soil hardness can make it difficult to perform this treatment in a timely and efficient manner, resulting in damage to the crop and yield reductions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cropro.2023.106301.

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