Resource efficient control of *Elymus repens*

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Cover: *Elymus repens* standing tall in a pea field
(photo: Björn Ringselle)

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Abstract

Elymus repens is a perennial grass weed that causes great yield losses in a variety of crops in the southern and northern temperate zones. Primary control methods for *E. repens* are herbicides or intensive tillage, both of which have a number of negative side-effects, e.g. herbicides can contaminate groundwater, and tillage can cause increased nitrogen leaching. The aim of this thesis was to investigate how to make non-herbicide control of *Elymus repens* more resource efficient in terms of less energy demanding soil cultivation and reduced nitrogen leaching. Three field experiments were used to test cover crop competition, mowing and different types of optimised tillage techniques and timing, as well as the combination of under-sown cover crops and mowing or row hoeing. The growth, biomass allocation and morphological responses of *E. repens* to competition were studied in a greenhouse experiment.

The effect of competition from under-sown cover crops on *E. repens* seems to depend greatly on the cover crop biomass achieved. At high biomass levels, the cover crop can be highly suppressive (Paper IV) and reduce nitrogen leaching (Paper III), while at low levels they can still provide benefits such as reduced *E. repens* shoot biomass and increased subsequent cereal yield (Paper I). However, a low-yielding red clover cover crop increased *E. repens* rhizome production by 20-30%. Under-sown cover crops were successfully combined with both mowing and row hoeing (Paper I & III), but while repeated mowing reduced *E. repens* rhizome production by 35% it could not be shown to give a competitive advantage to the cover crops over *E. repens* (Paper I). However, the low nitrogen leaching and reduced downward transport of nitrogen when mowing or row hoeing was combined with under-sown cover crops make them interesting control methods for future research. Delaying tine cultivation by a few days after harvest did not reduce *E. repens* control, but a delay by 20 days tended to result in higher *E. repens* rhizome biomass and shoot densities, compared to performing it within a few days of harvest. Repeated tine cultivation did not improve control of *E. repens* or increase subsequent cereal yield, compared to a single cultivation directly after harvest. Repeated cultivation during autumn should therefore not be used categorically, but only when there is reason to believe the shoots will pass the compensation point due to the autumn conditions. We conclude that a site specific approach is necessary to achieve resource efficient control of *E. repens.*

Keywords: Elytrigia repens, *Agropyron repens*, mowing, mechanical control, perennial weed, organic farming, nitrogen leaching, competition, cover crops, soil tillage

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Dedication

To Fereshteh, the most wonderful hunbun in the world

Efficiency is doing things right; effectiveness is doing the right things.
Peter F Drucker

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

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

II B Ringselle, G Bergkvist, H Aronsson & L Andersson. Importance of timing and repetition of stubble cultivation for post-harvest control of *Elymus repens* (submitted manuscript)

III H Aronsson, B Ringselle, L Andersson & G Bergkvist. Combining mechanical control of couch grass (*Elymus repens* L.) with reduced tillage and cover crops to decrease N and P leaching (submitted manuscript)

IV B Ringselle, L Andersson, H Aronsson, I Ruiz & G Bergkvist. Biomass allocation in *Elymus repens* as affected by competition from perennial ryegrass and red clover (manuscript)

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The contribution of Björn Ringselle to the papers included in this thesis was as follows:

I First author. Planned, performed and oversaw field and lab work. Analysed and interpreted results. Wrote the paper in cooperation with co-authors and responded to comments from reviewers.

II First author. Planned, performed and oversaw field and lab work. Analysed and interpreted results. Wrote the paper in cooperation with co-authors and responded to comments from reviewers.

III Co-author. Analysed and interpreted results. Contributed writing to introduction, statistical analysis and result section and commented on the remaining sections.

IV First author. Planned experiment and formulated the hypotheses in cooperation with co-authors. Performed, planned and oversaw lab work. Analysed and interpreted results. Wrote the paper in cooperation with co-authors and will be responsible for interaction with reviewers once it is submitted.

1 Introduction

Elymus repens (L.) Gould (couch grass) is a perennial weed tolerant of tillage and was long considered one of the most problematic weeds in the temperate zone. Its biology was extensively studied to develop effective mechanical control methods, especially in the 1960-1970's (e.g. Permin, 1960; Palmer and Sagar, 1963; Håkansson, 1967; Cussans, 1972). Many studies on chemical control were also performed (e.g. Bylteryd, 1958; Granström, 1960; Waterson *et al.*, 1964), but it was not until glyphosate was introduced in the 1970's that an effective and flexible chemical control of *E. repens* was found. Today glyphosate is in most of the most commonly used herbicides and it is still the primary control method for *E. repens*. Its low cost, especially after the expiration date of the patent, and large usefulness significantly reduced interest into alternative control methods in the decades following its introduction. However, the agro-ecosystem is constantly evolving as crops are introduced, new pest species appear and management techniques change to accommodate new technology, customer demands and concerns. As a consequence, old problems that were considered solved can resurface as circumstances change. The ever increasing pesticide dependence in modern agriculture has caused concerns about health risks, environmental pollution and pesticide resistant organisms. In recent years this has increased the popularity of organic agriculture and compelled the European Union to issue a directive on sustainable use of pesticides, stating that all member states should take action to implement integrated pest management (IPM); i.e. farmers should use pesticides as the last resort (2009/128/EC, European Commission 2015). In combination with a large number of herbicides being banned in the EU or internationally and few new modes of actions being discovered, this has resulted in limited options for many farmers. Perennials tolerant of tillage operations, like *E. repens*, is one group of weeds that clearly stands to benefit from reduced herbicide use. Their underground storage organs make them difficult to control without herbicides or intensive tillage. However, tillage is costly, fuel and time-consuming, sensitive to weather conditions and can increase nitrogen leaching. There is therefore a need for developing alternative control methods for these perennial weeds and/or devise tillage strategies with a higher degree of resource efficiency.

1.1 Overall aim

The aim of this thesis was to investigate how to make non-herbicide control of *Elymus repens* more resource efficient in terms of less energy demanding soil cultivation and reduced nitrogen leaching. Three field experiments were used to test cover crop competition, mowing and different types of optimised tillage techniques and timing, as well as the combination of cover crops and mowing or row hoeing. The growth, biomass allocation and morphological responses of *E. repens* to competition were studied in a greenhouse experiment.

Specific hypotheses can be found in section 1.4, divided into cover crops (1.4.1), the combination of mowing or row hoeing with cover crops (1.4.2) and optimal tillage (1.4.3).

1.2 *Elymus repens*

Elymus repens is a perennial grass with both seed and rhizome propagation (Fig. 1), both of which are integral to *E. repens* long-term persistence and dispersal within an ecosystem. Rhizomes are underground stems, which function as storage organs and support buds from which new shoots can emerge. Like other perennials, the stored energy enables persistency within a field even without a seedbank and gives a competitive advantage that many annual weeds lack, making it persistent even in perennial crops like leys. Many perennial weeds are vulnerable to defoliation and/or tillage which means they cannot persist in annual crops that are regularly tilled, but *E. repens* will quickly reshoot after destruction of shoots and/or fragmentation of rhizomes as long as they retain intact buds and enough energy to reshoot. Control of *E. repens* is therefore a time-consuming and costly war of attrition and even if it is successful, reestablishment by *E. repens* seeds from surrounding lands is likely. In the agro-ecosystem, *E. repens* is mainly a problem in the southern and northern temperate zones, including New Zealand, Australia, temperate Asia, Northern Europe, Canada, Russia and Northern USA. In grasslands *E. repens* competes with forage crops, but it is not poisonous to animals and provides relatively good nutrient balance in feed. In cropland, however, *E. repens* can cause great yield losses in both annual and perennial crops.

Figure 1 *Elymus repens* is a perennial grass with underground stems, rhizomes, used for propagation and storage (top left and bottom right). If uncontrolled it can rapidly go from a few plants (top right) to a major infestation (bottom left), especially in uncompetitive crops. Photos: Björn Ringselle

1.3 Control methods for *Elymus repens*

1.3.1 Mowed rotational leys

Ley crops are the most common crops in Swedish agriculture. They are mainly used to produce animal feed, but also to control weeds and increase the fertility of the soil. They typically consist of a mixture of different species, often grasses and legumes. The high competitive nature of the ley crop coupled with regular mowing, makes it a very effective control measure against primarily annual weeds, but even problematic perennial species such as *Cirsium arvense* (L.) Scop (Canadian thistle) and *Sonchus arvensis* L. (field sowthistle), tend to decrease as the ley ages (Håkansson, 2003). However, *E. repens* populations tend to stabilize or gradually increase within the ley, even with a relatively high cutting frequency (Cussans, 1973). Consequently, herbicides or intensive tillage is usually required to control *E. repens* after the ley is broken.

1.3.2 Herbicides

The most common herbicides used for control of *E. repens* contain glyphosate (N-(phosphonomethyl)glycine). It is cheap and if used at the right time it is transferred to the rhizomes, effectively killing the whole plant. As a consequence, the ubiquitous use of glyphosate has shifted *E. repens* away from being considered a major agricultural threat to a concern for primarily organic farming. However, there are risks associated with over-reliance on herbicides, such as herbicide resistance, which has been clearly demonstrated by the many examples of glyphosate resistant weeds (Heap, I. The International Survey of Herbicide Resistant Weeds). Also, there are the potential environmental problems associated with pesticide use, e.g. contamination of ground and surface water. Moreover, since regular spraying in conventionally managed fields is still necessary to prevent re-establishment, *E. repens* presents a major challenge for combining reduced and no-till systems with no or reduced herbicide use (Pollard and Cussans, 1977; Boström and Fogelfors, 1999).

1.3.3 Tillage

Tillage is the main alternative to herbicides and the predominant weed control method in organic farming. The soil is tilled by running a plough, harrow, hoe and/or some other implement through it. As a consequence any stubble or vegetation cover is destroyed and/or incorporated into the soil. This reduces the transfer of plant diseases from one crop to the next, prepares the soil for the subsequent crop, destroys current weed shoots and can damage and/or displace seeds, rhizomes and roots.

When used to control *E. repens*, the aim of tillage is to kill the shoots, fragment the rhizomes and bury them deeper in the soil or to pull them above ground. Once on the ground they can either be collected or left to desiccate (Melander, 2013), if soil surface conditions are dry enough. Rhizome fragmentation results in smaller rhizomes which increase the number of buds that produce shoots (Permin, 1973). Moreover, the smaller the rhizomes are and the deeper they are buried, the fewer and the less competitive the emerging shoots will be (Håkansson, 1968).

Ploughing is often the main mechanical control method, which buries the rhizomes deeply in the soil. Both autumn and spring ploughing reduce *E. repens* rhizome biomass (Chandler *et al.*, 1994), but to achieve satisfactory control ploughing is frequently combined with repeated stubble cultivation

(Cussans and Ayres, 1977; Boström and Fogelfors, 1999); to weaken *E. repens* before ploughing by destroying the shoots and fragmenting the rhizomes. Repeated stubble cultivation takes advantage of the large sprouting capacity of fragmented *E. repens* rhizomes (Liew *et al.*, 2013). Cultivation should be repeated at or before *E. repens* reaches the compensation point which occurs at the 3-4 leaf stage in unshaded *E. repens* plants (Håkansson, 1969a). This prevents the rhizomes from increasing their energy reserves and reshooting results in a net energy loss.

1.3.4 Negative effects of mechanical control

Cost from tillage is generally made up of direct costs like energy consumption, work hours and machine maintenance, and indirect costs like soil compaction, nutrient leaching and CO_2 emissions. In general, the deeper the tillage and the more compact the soil, the more energy and time will be required. If fossil fuels are used it will directly contribute to greenhouse gas emissions.

Due to time constraints during the spring and the presence of a crop during the summer, autumn is often the only available time for mechanical *E. repens* control. In cold climates, leaching mainly occurs during autumn and winter (Thorup-Kristensen *et al.*, 2003). Tillage in early autumn, which stimulates mineralization and accumulation of mineral N in the soil, thus increases the risk of N leaching (Hansen and Djurhuus, 1997; Stenberg *et al.*, 1999; Catt *et al.*, 2000; Mitchell *et al.*, 2000).

To reduce the direct and/or indirect costs of the mechanical control of *E. repens*, the number and/or intensity of the tillage operations has to be reduced or they have to be performed in such a way or at such a time that it maximises the control of *E. repens* while minimizing the costs.

1.4 Potential resource effective control methods: cover crops, mowing and optimised tillage

1.4.1 Cover crops

Cover crops are either sown into/with a main crop, or after harvest of the main crop. Often they are used to reduce erosion and nutrient leaching during autumn and winter (Hartwig and Ammon, 2002). Furthermore, cover crops can reduce weed growth, increase soil organic matter content, soil microbial activity, increase water retention and improve the soil structure (Hartwig and Ammon, 2002). The positive effects will vary depending on the traits of the species used, the environmental conditions and the success of its establishment and growth. For example, legumes can fix atmospheric nitrogen, which can benefit subsequent crops (Bergkvist *et al.*, 2011). Other cover crops (e.g.

grasses) will compete for nitrogen at all levels of availability and are therefore better at and more consistent in reducing leaching (Breland, 1996). The aim will consequently influence which species or mixture are the most suitable. A potential control method for *E. repens* is to use cover crops to compete with the weed in periods without a main crop, or to enhance the competitive effect of the main crop. It would essentially function like a short-term ley; either control the weed or slow its growth.

Cover crops have been shown to be capable of reducing or even controlling both annual and perennial weeds (Teasdale *et al.*, 2007). For example, in experiments by Popay *et al.*, (1993), cover crops under-sown in wheat (*Triticum aestivum* L.) reduced the number of *Rumex obtusifolius* L. seedlings by 70% in the following year. However, the effect varies considerably depending on establishment success and cover crop species used, especially the effect on highly competitive weeds such as *E. repens*. Some authors have found no effect at all (e.g. Popay *et al.*, 1993; Brandsæter *et al.*, 2012; DEFRA, 2011; Melander *et al.*, 2013) with cover crops such as perennial ryegrass (*Lolium perenne* L.), red clover (*Trifolium pratense* L.), white clover (*Trifolium repens* L.), and a mixture of fodder radish (*Raphanus sativus* L.) and Westerwolds ryegrass (*Lolium multiflorum* Lam. var. westerwoldicum). Others report 20-70% reduction in shoots and/or rhizomes (Cussans, 1972; Dyke and Barnard, 1976; Bergkvist *et al.*, 2010; DEFRA, 2011) with red clover, red fescue (*Festuca rubra* L.), perennial ryegrass, Italian ryegrass (*Lolium multiflorum* Lam.), oilseed rape (*Brassica napus* L.) and buck-wheat (*Fagopyrum esculentum* Moench).

In the experiments presented here we used two species as cover crops – perennial ryegrass (*Lolium perenne* L.) and red clover (*Trifolium pratense* L.). We hypothesized that both cover crops would reduce *E. repens* biomass, but that perennial ryegrass would be a more effective competitor to *E. repens* than red clover and that the mixture of ryegrass and red clover would be as competitive as pure ryegrass, but have a greater positive effect on subsequent cereal grain yield (Paper I). Moreover, competition from perennial ryegrass was predicted to increase the allocation of *E. repens* towards belowground biomass, while red clover was predicted change it towards aboveground biomass (Paper IV).

1.4.2 Combining cover crops with mechanical control: mowing and row hoeing

Two potential control methods for *E. repens* which could be combined with cover crops are mowing and row hoeing. Mowing in this sense refers to mechanically cutting the vegetation cover. Consequently, both weeds and cover crops are cut, but not killed as would be the case with tillage. Moreover, compared to tillage, mowing uses little energy and does not disturb the soil, so there is less risk of nitrogen leaching (Mitchell *et al.*, 2000). However, plant material exposed to freeze-thaw cycles during winter can increase leachable phosphorous, so if the cut material after mowing is not collected, the risk of phosphorous leaching is increased (Bechmann *et al.*, 2005; Sturite *et al.*, 2007; Liu *et al.*, 2013). In meadows and leys, cutting for hay or silage has a strong controlling effect on most weeds common in systems with annual crops. By removing the shoots, mowing will reduce *E. repens* rhizome growth, but not as much as tillage and it will not kill the plants, except with very frequent mowing (Håkansson, 1969a). The mowing effect slows with increasing rhizome size and varies depending on available nitrogen; higher nitrogen levels increase growth, which in turn empties the rhizomes faster at high mowing frequencies (Turner, 1966). One of the morphological traits which *E. repens* uses to deal with repeated defoliation is heavy tillering, which competition from cover crops could help reduce (Håkansson, 1969a). The weed would thereby be stimulated to produce fewer and larger shoots in the presence of cover crops, making it more vulnerable to mowing. If the cover crop is not damaged by the mowing to the same extent as *E. repens*, the effects of mowing and competition are likely to be synergistic.

Row hoeing is a method for performing tillage in a growing crop, usually with increased row distance and tillage between the rows. If the cover crops are sown together with the main crop in the rows, the cover crop will be spared while any weeds between the rows are tilled. In theory, the high controlling effect of tillage would therefore be combined with a competitive cover crop capable of both reducing *E. repens* biomass and nitrogen leaching.

We hypothesized that mowing would have a greater negative effect on *E. repens* than on the cover crops, and therefore the combined effect of both mowing and cover crops would be synergistic (Paper I). Moreover, we predicted that cover crops in combination with mowing and row hoeing would reduce *E. repens* biomass without increasing nitrogen leaching, while mowing would increase phosphorous leaching compared to the other treatments (Paper III).

1.4.3 Optimised tillage

Tillage has been shown to be an effective control method for *E. repens*, especially repeated stubble cultivations followed by ploughing (Cussans and Ayres, 1977; Boström and Fogelfors, 1999). However, by optimising the time of cultivation, the type of cultivation and the frequency of cultivation, much could be gained in reducing nitrogen leaching and cost, time- and fuel consumption without necessarily sacrificing the efficacy of the *E. repens* control.

Due to time constraints during spring and the presence of a crop during the summer, the period after harvest in autumn is often the first suitable time for mechanical *E. repens* control. Delaying cultivation is problematic since intact *E. repens* plants can drastically increase their rhizome biomass during the post-harvest period (Boström *et al.*, 2013). Despite this, farmers may postpone stubble cultivation by days or even weeks after the harvest because of time constraints during harvest, giving *E. repens* more time to store resources. Due to the reported weak seasonal dormancy of *E. repens* buds (e.g. Brandsaeter *et al.*, 2010), it has been assumed that the rhizome starvation effect of repeated stubble cultivation is similar throughout the vegetation period. However, Liew *et al.* (2013) found that the fragmented rhizomes of some *E. repens* populations had a lower tendency to produce shoots during September-October than earlier and later in the autumn. This indicates that stubble cultivation might be less efficient during this period. Furthermore, since most studies test only repeated cultivation (e.g. Cussans and Ayres, 1977; Boström and Fogelfors, 1999) or a single cultivation (e.g. Landström, 1980) they cannot be used to conclude whether the repeated cultivations during autumn enhances the controlling effect beyond simply preventing autumn growth.

We hypothesized that when combining tine cultivation with ploughing, a delay of the first cultivation after harvest by 5-20 days would reduce *E. repens* control compared to performing it directly after harvest (Paper II). Cultivating twice was predicted to reduce *E. repens* more than cultivating once (Paper II & III), but also result in more nitrogen leaching than cultivating once (Paper III).

2 Material and method

Three multi-locational field experiments and one greenhouse experiment were used to investigate a number of control methods for *E. repens* with the potential for low nitrogen leaching and low energy demand. Field experiments are labour intensive and must be run multiple years and preferably at several locations to account for weather and soil variation, but are essential for capturing treatment effects in real world conditions. The greenhouse experiment was used to complement the field experiments by testing the effects of competition in a more controlled environment with fewer distracting factors.

Sampling times are given in table 2 and treatments in table 3.

2.1 Experimental design

Each field experiment used their own experimental protocol for two rounds of the same experiment; 2011-2012 (Experimental round 1, ER1) and 2012-2013 (ER2). The first year was the treatment year (Y1) when initial *E. repens* population size was measured and control measures were imposed. The second year was the residual year (Y2) during which effects of the treatments was evaluated. Thus, ER1Y1 denotes the treatment year of experimental round 1. The greenhouse experiment was conducted in the spring of 2014.

The first field experiment (Paper I) focused on cover crop competition and mowing, alone and in combination. The second field experiment focused on timing and frequency of autumn tillage (Paper II). In the third field experiment, separately tile-drained plots for measurements of nutrient leaching were used to investigate the combination of cover crops and mowing used in the first experiment and the stubble cultivation used in the second experiment, as well as row hoeing (Paper III). In the greenhouse experiment (Paper IV) the aim was to explain the competitive effect of cover crops on *E. repens* as shown in the cover crop/mowing experiment (Paper I). Thus, the effects of competition for light and nutrients on *E. repens* were investigated more closely than could be achieved in the field experiment.

2.2 Field sites

Fields on farms using organic farming practices and with a natural population of *E. repens* were chosen for the field experiments. They were located at farms outside Uppsala in eastern Sweden, outside Hässleholm in southern Sweden (Paper I & II) and at Lilla Böslid experimental farm in southwest Sweden (Paper III). The Uppsala sites have a high percentage of clay and silt, Hässleholm a large degree of sand, silt and soil organic material, while the Lilla Böslid site is dominated by sand. All plots at Lilla Böslid are equipped for continuous measurements of drainage water flow and flow-proportional water sampling. The greenhouse experiment was conducted at SLU's campus in Ultuna, Uppsala (Paper IV).

2.3 Sampling and measurements

2.3.1 Sampling *E. repens*

Accurately sampling *E. repens* can be difficult, just like with other perennial weeds (Turner and Cussans, 1981). The competitive influence it exerts on the concurrent crop is most likely based on shoot and root biomass. Future problems, however, is primarily based on the rhizome biomass amount and production, and to some degree the seed production. Consequently, to obtain a representative measure of the *E. repens* population and the effects of treatments may require multiple complementary measurements of both above and belowground biomass or even morphological features.

Taking a large number of samples during the year in multiple locations is very labour intensive, especially for certain types of biomass such as roots. Therefore, while shoot and rhizome biomass was collected in all experiments, root biomass and morphological features were only measured in the greenhouse experiment (Paper IV). Rhizome biomass was collected with a golf hole drill and biomass cut by hand within 0.25 m^2 frames (Fig 2). In addition to measuring biomass, a novel tool called a grading fork (Fig. 3) was used in the field experiments to measure shoot density. It gives an ordinal value between 0 and 3, and thus cannot be used to quantify the *E. repens* population size. However, it provides a quick and easy way to measure *E. repens* abundance and can therefore be used for collaborating any apparent trends and patterns caused by the treatments.

Table 2 Sampling times for E. repens abundance and soil mineral nitrogen for both experimental rounds (ER) and years (Y1 and Y2) in the three field experiments presented in Paper I, II and III. Drainage water and N/P concentrations was measured continuously throughout the years in the experiment presented in Paper III

	Shoot density	Rhizome biomass	Shoot biomass	Crop grain yield	Soil mineral nitrogen	Drainage water, N & P conc.
Spring Y1	I, II, III					III
Harvest Y1	I, II, III	I, II, III	I, III	I, II, III	I, III	III
Early autumn Y1	I, II, III				III	III
Late autumn Y1	I, II, III		I, III		I, III	III
Spring Y2	I, II, III					III
Harvest Y2	I, II, III	I, II, III	I, II, III	I, II, III		III
Early autumn Y2	I, II, III					III

Figure 2 Aboveground biomass was cut by hand inside a 0.25 m^2 frame, sorted and dried (top). Rhizome biomass was collected with a golf hole drill, cleaned and dried (bottom). Photos: Björn Ringselle

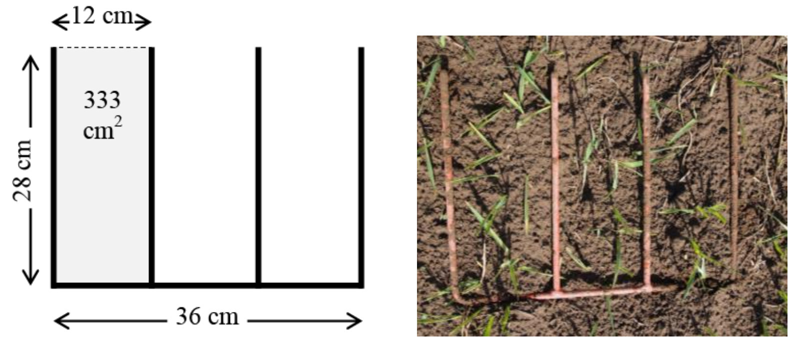


Figure 3 Grading fork (36x28 cm) with four tines for measuring *Elymus repens* shoot density. Gives a score between 0-3, depending on whether the intertine areas contain shoots or not. Photo and drawing: Björn Ringselle

2.3.2 Measuring nutrient competition and leaching (Papers I, III & IV)

Nitrogen concentration (Paper I & IV) in *E. repens* shoots was measured to determine competitive effect of the cover crops on *E. repens*. Soil mineral nitrogen was measured at multiple soil layers by using a tube drill (Paper I & III) and drainage water and nitrogen and phosphorus concentrations were continuously measured using the separately tile-drained plots at Lilla Böslid (Paper III). Thus it was possible to evaluate the effect of cover crops and mechanical treatments on the nutrient availability in the different soil layers and their leaching rate throughout the year.

2.4 Mechanical treatments and tools

Mowing was performed using agricultural mowers that cut biomass at a designated height (Paper I & Paper III). Stubble cultivation was conducted using cultivators/harrows with tines (Paper I & III) and discs (Paper III). The tines/discs are run through the soil to loosen it, break up the stubble and/or destroy weeds (Fig. 4). Both tines and discs can vary in size, design and number, and can be run at different angles, speeds and depths in the soil. The tines can be narrow (Paper I), or have attachments that broadens them, e.g. duckfoot tines (Paper III) (Fig. 4). Discs are more effective at cutting up rhizomes than the tines, which tend to drag larger chucks through the soil and above ground.

Table 3 Combination of cover crops and mechanical control in treatments across the three field experiments (Papers I-III) and the greenhouse experiment (Paper IV). Mechanical treatments were performed one or two times during the autumn. Depth in the soil of mechanical control is given within parenthesis. All plots in the field experiments were ploughed in late autumn

Cover crops	No mech. control	Mowing		Row hoe		Disc harrow (10-12 cm)		Tine cultivator (10-12 cm)		Duckfoot cultivator (7 cm)	
		One	Two	One	Two	One	Two	One	Two	One	Two
None	All	I	I				III	II*	II*	III	III
Clover	I, IV	I	I								
Ryegrass	I, IV	I	I								
Mixture	I	I	I, III		III						

*In Paper II not only the number of treatments, but also the timing of the treatments was an important aspect. What happens to the control effect of *E. repens* if the cultivation is delayed 5-20 days after harvest?

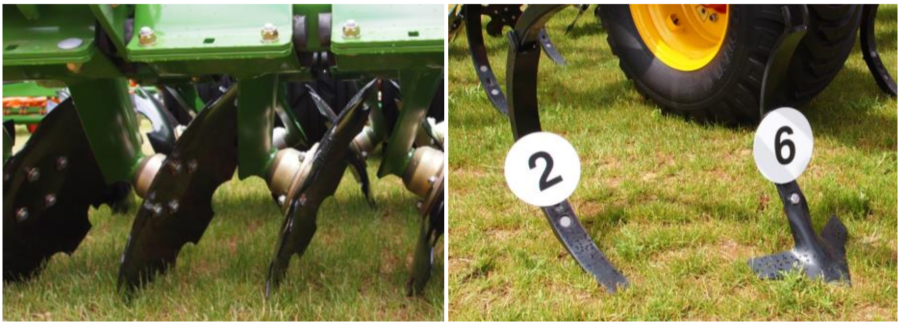


Figure 4 Discs (left picture) vs. tine and duckfoot (nr 2 and 6 in the right picture, respectively). Photos: Björn Ringselle

3 Results and discussion

3.1 Evaluation of methods for sampling *E. repens* abundance

The methods we used for sampling *E. repens* abundance were satisfactory for the most part. As long as the soil was not too compacted (the heavy clay soil making rhizome sampling near impossible was one reason a site was dropped from Paper II), the golf hole drill proved a quick and relatively easy way to extract rhizome biomass (Fig. 2). Frequent repairs of the drills was necessary however, as they were not designed to handle field work and broke down on a regular basis. Aboveground cutting is a tried and tested technique and the main drawback could be said to be the feeling of sitting in a field in the middle of nowhere in sweltering heat, surrounded by buzzing insects and cutting away your only source of shade.

The grading fork (Fig. 3) was designed as a quick and dirty way to measure *E. repens* shoot density. As such it can be said to have worked well. A 68 plot site with ten sample points per plot could be finished by one person in one day. This can be compared to rhizome or biomass sampling which may take four times as many work hours, or more, and generally required multiple people. Not to mention the time necessary for cleaning, drying and weighing the biomass samples. The main drawbacks of the grading fork method are that (i) it gives ordinal data which is impossible to quantify, (ii) it has a limited range, so it cannot accurately differentiate between high density stands that all have the highest value, and (iii) it will give no information on the size or development stage of the shoots. For all these reasons, the grading fork should only be used to complement other forms of measurements such as biomass sampling. In fact, it seems to have been worthwhile to sample both multiple types of abundance and during both experimental years. For example, sampling of *E. repens* shoot biomass and density in the treatment year, and rhizome biomass in the residual year, showed very clearly that treatments that reduce aboveground biomass in the autumn, does not necessarily have a long term effect on *E. repens* (Paper I). Changes in the allocation pattern towards or away from the shoots may also cause over- or underestimation of the rhizome biomass when sampling *E. repens* shoot biomass (Paper IV).

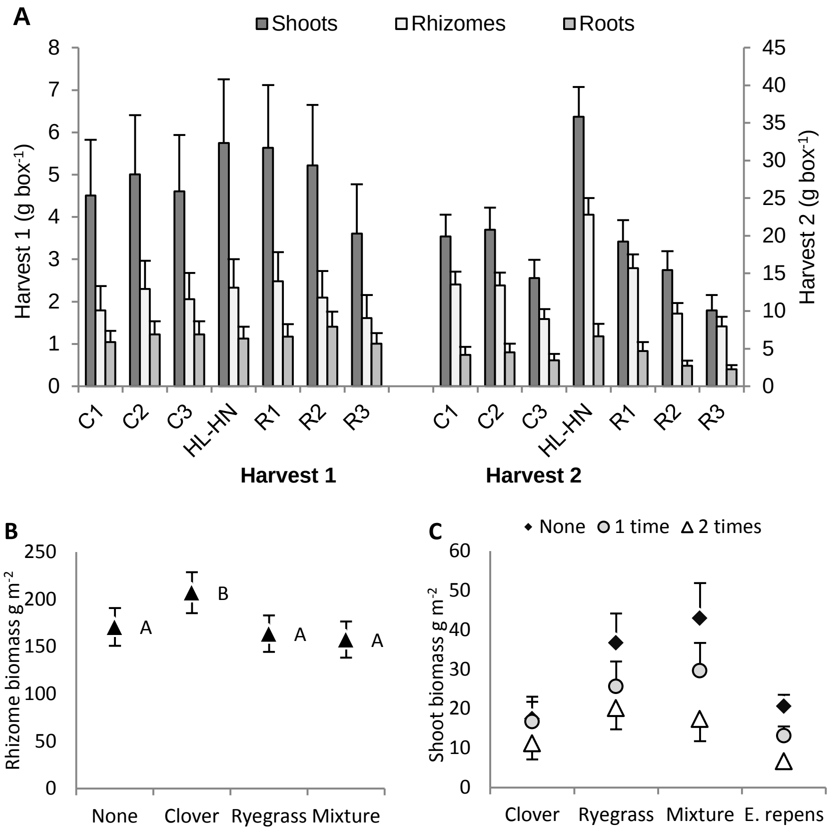


Figure 5 (A) Effects of increasing red clover (C1<C2<C3) or perennial ryegrass densities (R1<R2<R3) on *E. repens* shoot, root and rhizome biomass compared to no cover crop (HL-HN), 42 days and 72 days after sowing (harvest 1 and 2, respectively). (B) Residual effect in Y2 from cover crop competition from red clover, perennial ryegrass or the mixture of the two on *E. repens* rhizome biomass. (C) Effect of mowing no, one or two times on cover crop biomass and *E. repens* biomass during late autumn Y1.

3.2 Cover crops

High-yielding cover crops can reduce production of both above and belowground biomass in *E. repens* (Fig 5A; Paper IV; Cussans, 1972;

Bergkvist *et al.*, 2010). If the cover crop biomass is too low, however, there is negligible reduction in rhizome biomass (e.g. Brandsæter *et al.*, 2012; Melander *et al.*, 2013), even if the shoot biomass is reduced, as in our field experiment (Paper I). A contributing factor may be that cover crops heavily competing for nutrients can shift the allocation rate towards the belowground biomass (Paper IV), either because *E. repens* is trying to avoid competition by sending out rhizomes, or increasing storage to promote long term persistency. Furthermore, when using a cover crop of only legumes, there is a risk that a low-yielding cover crop will actively benefit *E. repens*. For example, red clover increased *E. repens* rhizome biomass in the subsequent year by 20-30%, compared to no cover crop, perennial ryegrass or a mixture of red clover and ryegrass (Fig 5A; Paper I). This may be due to *E. repens* using the nitrogen fixated by the clover, just like subsequent crops do (Bergkvist *et al.*, 2011). In contrast, a mixture of ryegrass and red clover did not increase *E. repens* rhizome biomass, but instead reduced *E. repens* shoot biomass and increased subsequent cereal yield (Paper I). In addition, the mixture had a more consistent cover crop biomass across sites (Paper I), indicating that ryegrass compensated for a weak red clover establishment, and vice versa. A mixture should therefore generally be preferable to a single species cover crop, especially if it is a legume.

3.3 Combining cover crops with mechanical control: mowing and row hoeing

Mowing reduced *E. repens* shoot biomass, and if it was repeated reduced rhizome biomass by 35%, compared to no mowing (Paper I). However, combining mowing with a cover crop did not result in a higher reduction of *E. repens* biomass than cover crop biomass (Fig. 5C), and no enhanced controlling effect of *E. repens*, compared to competition from a not mowed cover crop. Rather the interaction between mowing and cover crops in autumn showed a reduced control effect of a single mowing of ryegrass or mixture compared to mowing twice or not mowing (Paper I). Thus, the cover crops did not gain a competitive advantage over *E. repens* from the mowing, and consequently no synergistic effect could be found (Paper I). Moreover, perennial ryegrass changed *E. repens* allocation towards belowground biomass (Paper IV), though it is difficult to say whether that would make it less vulnerable to mowing since fewer resources will be lost, or more vulnerable to mowing since those resources are proportionally more important for producing the necessary photosynthesis for survival and growth.

Due to the great variation in control effect among treatments, row hoeing could only be shown to decrease *E. repens* shoot density (Paper III). Thus, further research is necessary to show the viability of row hoeing combined with cover crops as a control method for *E. repens* and other weeds.

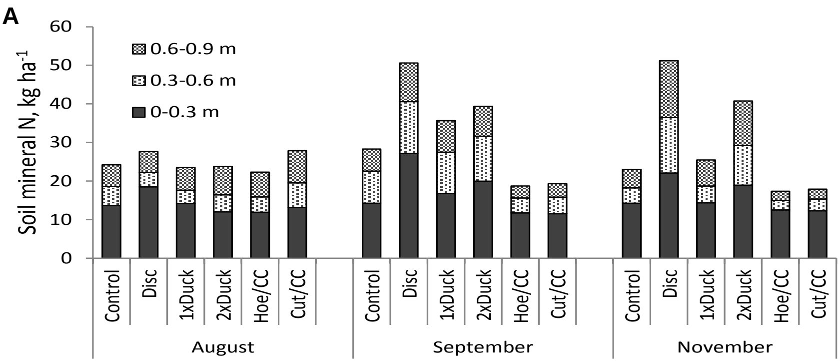
In regards to nitrogen leaching, both mowing and row hoeing in combination with cover crops showed very promising results. They slowed the downward transport of nitrogen and had nitrogen leaching comparable with control (Fig. 6A; Paper III). There was a trend towards increased phosphorous leaching when mowing, but this could potentially be avoided by collecting the cut plant material after mowing (Paper III).

3.4 Optimised tillage

Stubble cultivation performed five days after harvest or earlier reduced *E. repens* more than delayed stubble cultivation 20 days after harvest (Fig. 6B; Paper II). Additional tine cultivation 20 days after harvest did not improve subsequent spring cereal yield or *E. repens* control compared to a single tine cultivation performed directly after harvest (Fig. 6B; Paper II). A single early cultivation with a duckfoot cultivator had both less soil mineral nitrogen and less nitrogen leaching compared to the repeated cultivation with duckfoot or disc (Fig. 6A; Paper III). While not immediately transferable to the tine cultivator used at a slightly lower depth in Paper II, this still indicates that it is possible to reduce the number of cultivations during autumn and therefore have less nitrogen leaching, without necessarily sacrificing *E. repens* control. Not only that, but as the second tine cultivation did not actually provide any additional control, this indicate that it is more important to prevent *E. repens* autumn growth, rather than starving it with cycles of cultivations and reshooting.

During early autumn, after the main crop has been harvested, intact *E. repens* plants can drastically increase the size of their rhizome network (Boström *et al.*, 2013). By disrupting the *E. repens* plants as early as possible post-harvest and keeping them below the compensation point, not only is this rhizome growth prevented, but respiration will cause a net loss of energy storage during the autumn period. A successful resource efficient cultivation in autumn is not then defined by how much reshooting it can cause, but rather the opposite; reshooting should be delayed as much as possible to prevent *E. repens* from reaching the compensation point. The longer reshooting can be delayed the lower the light intensity and the shorter the photoperiod will be, resulting in lower overall biomass production and higher allocation to aboveground biomass (Palmer, 1958; Håkansson, 1969b; Skuterud, 1984).

Consequently, we conclude that repeated cultivation should not be used categorically, but rather when there is reason to believe that the emerging shoots will contribute to a significant build-up of rhizome biomass. For example, at sites and in years with a longer and/or milder autumn period, new *E. repens* shoots may have time to pass the compensation stage in the absence of additional treatments.



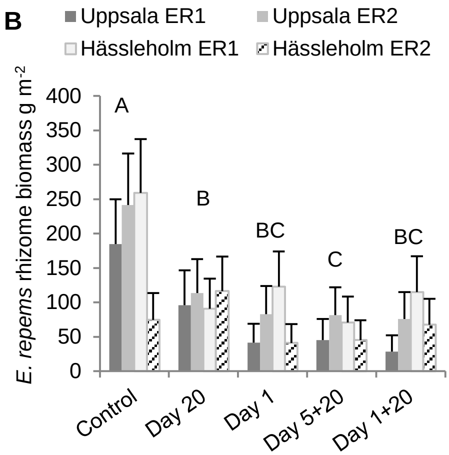


Figure 6 (A) Treatment effects of repeated disc harrow, single and repeated duckfoot cultivator and cover crops in combination with row hoeing or mowing on soil mineral nitrogen in August, September and November in Y1, compared to only ploughing (control). (B) Residual effect in Y2 of tine cultivation performed once twenty days after harvest (Day 20), once directly after harvest (Day 1), five days after harvest and twenty days after harvest (Day 5+20) and directly after harvest and twenty days after harvest (Day 1+20), compared to only ploughing (Control).

3.5 Concluding remarks and future research needs

The challenge in this thesis has not been to find the most effective control methods of *E. repens*, but the most resource efficient. It is inescapable that there are already effective ways of controlling this perennial weed. The problem is not that these control methods have stopped working, but rather the costs and negative side-effects associated with them. A further consideration is that the agricultural system does not live or die depending on *E. repens* control. It is one of countless things that farmers have to take into account when they plan their farming strategies. Thus, an important aspect to keep in mind is not only the effectiveness of the control, but also the flexibility of how it can be applied and how it can be combined with other measures; whether these measures deal with weed control, nutrient conservation, yield or any of the other thousands of things that farmers have to care about.

The experiments shed light on the difficulties with controlling *E. repens* with cover crops, as well as leys. It is difficult to achieve a consistently large cover crop biomass that reduces *E. repens* rhizome biomass. Also, it seems that pure legume cover crops should not be used against *E. repens* since there is a risk that it will increase rhizome production. Moreover, mowing does not seem to benefit the tested cover crops more than *E. repens* and the effect of repeated mowing was weaker on *E. repens* than cultivation (Paper I), which could explain *E. repens* persistence in mowed leys. However, there is a great deal of work that could be done to potentially improve the results, including but not limited to; different mowing heights and frequencies, more selective mowing, identifying more mowing compatible cover crops, more complimentary cover crop mixtures etc.

It was confirmed that it was possible to combine a vigorous cover crop with both mowing and row hoeing and that these did have a positive influence on nitrogen leaching (Paper III). This is very encouraging considering the many other benefits the ryegrass and mixed cover crop showed at relatively low biomass levels, such as reduced *E. repens* shoot biomass, tillers and shoot density, reduced general weed growth (data not shown) and/or increased subsequent cereal yield (Papers I & IV). Thus, even if the cover crops cannot be made to provide consistent and powerful suppression of *E. repens*, there seems to be clear incentive for designing control methods that can include them. Even if mowing and/or row hoeing cannot provide similar control as more intensive tillage, they may still be advisable in systems with small *E. repens* populations or systems with an increased risk of nitrogen leaching.

The investigation into optimised tillage revealed a number of interesting observations. Firstly, that delaying the cultivation to a few days after harvest did not seem to have any adverse effect on control of *E. repens* (Paper II). Which is exceedingly good news for busy farmers that have to choose between finishing the harvest or stubble cultivate. Secondly, the fact that additional cultivation did not seem to add any further control effect on *E. repens* (Paper II). Seemingly this goes directly against the advice to starve the rhizomes by repeated cultivations. However, it is exceptionally difficult to differentiate between starvation caused by continuous reshooting and starvation caused by the absence of photosynthesis. For the tine cultivators we used, which has a lower fragmentation effect than disc harrows, it seems that the reshooting was not fast enough for *E. repens* to reach the compensation point before ploughing to expand its rhizome biomass, which would have made a repeated cultivation effective. With finer fragmentation, *E. repens* might reshoot more or faster or make the fragments so vulnerable that repeated cultivation is worthwhile. Further experiments will have to determine if repeated disc cultivation generally provides a higher degree of control than single tine cultivation, but even if that is the case it will most likely not be more resource efficient. Any potential increase in controlling effect would have to be balanced against the demonstrated lower nitrogen leaching of a single cultivation, as well as the energy demand, work hours and other costs associated with additional cultivations.

If additional treatments are necessary to prevent *E. repens* from reaching the compensation stage, it may not be necessary to use another stubble cultivation. For example, if there is not that much time left in the autumn period, mowing could be an effective, but less intensive alternative to a second stubble cultivation. Earlier ploughing may also be an alternative. Ploughing would then interrupt the growth of *E. repens* in addition to burying the fragmented rhizomes at the ploughing depth.

In conclusion, a more site-specific approach is necessary to achieve more resource efficient *E. repens* control. Cover crops with mowing or row hoeing can most likely be used if it is only necessary to prevent *E. repens* growth, or if there is a great risk of nutrient leaching. If *E. repens* needs to be controlled by cultivation, it should then be determined whether the autumn conditions in that year and site require additional disturbances to prevent *E. repens* rhizome growth. After that one can choose whether that disturbance has to be another stubble cultivation, earlier ploughing, or if a less intensive method (e.g. mowing) can be used to prevent growth until the ploughing or winter. The time of harvest, the environmental conditions and the size of the *E. repens* population may be key to making that judgement.

The results presented here could lead to more resource efficient *E. repens* management strategies within both organic and conventional farming. However, there are still a large number of unexplored areas when it comes to resource efficient control of *E. repens*. For example, there is a need for further research into how weather and light conditions during autumn, initial *E. repens* population size and various tillage implements affect both the reduction in rhizome production and the re-establishment time of *E. repens* after tillage. Further testing and development of cover crops, mowing and row hoeing techniques may also be necessary to make them consistent control methods for *E. repens*.

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