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Combining mechanical rhizome removal and cover crops for *Elytrigia repens* control in organic barley systems

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Summary

Mechanical weed control of perennial weeds in organic crop production over long post-harvest periods is incompatible with the establishment of cover crops for improving soil quality and preventing nutrient leaching. We suggest a new concept that comprises uprooting and immediate removal of vegetative propagules located within the plough layer to allow for quick re-establishment of a plant cover. A field experiment comparing the effects of conventional practices (stubble cultivation) with different combinations of rotary cultivation (One, Two or four passes) and cover crops (none vs. rye-vetch-mustard mixture) on *Elytrigia repens* rhizome removal, shoot growth and suppression of a subsequent barley crop was examined in two growing seasons. Four passes with a modified rotary cultivator, where each pass was followed by rhizome removal, reduced *E. repens* shoot growth in barley by 84% and 97%. In general, the cover crop developed poorly and did not affect barley or *E. repens*. Barley yield was only affected by treatments in the first season, where yield was negatively correlated with *E. repens* shoot biomass. The concept has potential for the control of severe *E. repens* infestations, but future research aimed at identifying more effective smother crops and less intensive methods of rhizome removal is needed.

Keywords: perennial weeds, couch grass, rhizome, uprooting, removal, below-ground propagule, cover crop.

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Introduction

There is a need to rethink current practices to control *Elytrigia repens* (L.) Desv. ex Nevski in organic farming in Northern Europe. Infestations with *E. repens* are traditionally controlled by repeated stubble cultivation in the post-harvest period from harvest to ploughing. However, post-harvest tillage is undesirable due to the need for retaining nutrients, particularly nitrogen, in organic cropping systems (Melander *et al.*, 2011). Nutrient losses through leaching can be substantial in the humid North European climate prevailing in autumn and winter, if the soil is tilled and left bare without a cover crop. For example, nitrogen losses averaged 55 kg ha^{-1} in Danish long-term crop rotation experiments following repeated stubble cultivation to control perennial weeds. In contrast, nitrogen losses averaged 20 kg ha^{-1} where a cover crop was grown including significant reductions in the loss of potassium from a coarse sandy soil at one of the sites studied

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(Askegaard & Eriksen, 2008; Askegaard *et al.*, 2011). Nutrient losses are particularly problematic on farms with limited access to manure, often leading to low-yielding crops exerting poor suppression on weeds.

The management of nutrients and perennial weeds in organic arable cropping thus calls for a compromise in which effective weed control is achieved within a short time span after crop harvest to allow the re-establishment of a plant cover (Melander *et al.*, 2011). This may not be possible with all perennial weed species posing problems, but the prospects for substantial uprooting and removal of *E. repens* rhizomes appear promising. Rhizomes of *E. repens* are mainly located within the plough layer of 0–20 cm soil depth with hardly any rhizomes found below 20 cm (Håkansson, 1969; Lemieux *et al.*, 1992). This contrasts with other perennials that have roots or rhizomes penetrating the soil more deeply, such as *Cirsium arvense* (L.) Scop. and *Tussilago farfara* L. Tine or disc-based stubble cultivators only partly uproot below-ground propagules, with the fragmentation of rhizomes and roots being the most important effect. In Danish tests of different tool configurations and their abilities to uproot *E. repens* rhizomes, only power take-off (PTO)-driven rotary cultivators were applicable for uprooting purposes; one pass on a coarse sand could uproot almost half the rhizome biomass (Melander *et al.*, 2008; Pedersen, 2010). A supplementary test in which two and four passes with a rotary cultivator, followed by removal with a rotary rake of the exposed rhizomes after each pass, resulted in 63% and 93% removal respectively (Nørremark *et al.*, 2012; B Melander, unpubl. obs.). The rhizome biomass that remained in the soil after treatment declined exponentially with the number of passes, implying that complete uprooting may not be attained with a vertically rotating tilling device. Even small amounts of residual rhizomes may produce substantial shoot biomass in the subsequent year, because intra-competition between *E. repens* shoots with ample space is smaller than in denser stands. However, the importance of remains of rhizomes for the recovery of *E. repens* in a subsequent crop was not studied. The tests also revealed that multiple passes loosened and aerated the soil considerably. Coarse sandy soils with high pH values often experience manganese deficiency when tilled intensively and that can adversely affect crop growth (Norwell, 1988). This drawback needs attention and may require specific measures to compact the soil to an appropriate density to minimise oxidation of manganese.

The establishment of a cover crop immediately after uprooting rhizomes may further strengthen the overall control effect against *E. repens*. A dense and fast growing cover crop can suppress shoots emerging from remaining rhizome fragments (Graglia *et al.*, 2006; Teasdale *et al.*, 2007). The more efficiently a cover crop absorbs light, nutrients and water, the more weeds are suppressed (Hartwig & Ammon, 2002). A vigorous post-harvest ground cover also serves other agronomic goals, such as improved soil fertility and reduced erosion. Improved soil fertility and the release of nutrients from decomposing cover crop plant materials can strengthen crop growth and yield, resulting in a stronger suppression of *E. repens* shoots that may have survived the treatment from the previous year.

This study aimed at investigating the effects of rapid post-harvest rhizome uprooting and removal followed by growing a cover crop on *E. repens* shoot growth and the yield of a subsequent crop. We hypothesised that (i) shoot biomass production from residual rhizome biomass the year after uprooting is proportional to the remaining rhizome biomass, (ii) growing a cover crop immediately after uprooting will further reduce *E. repens* shoot biomass production and enhance the yield of a succeeding crop and (iii) the penetration resistance of the soil can be restored through modified seedbed preparation, despite the loosening caused by uprooting tillage.

Materials and methods

Experimental layout and treatments

The investigation was based on one experiment that was conducted twice, in 2009/2010 and 2010/2011. The experiment (expt) was established on a coarse sand at Jyndevad Experimental Station (54°54′N, 9°07′E) in August 2009 and then again in August 2010 on an adjacent area. Both areas had been cropped according to organic standards for several years and had a large and uniform population of *E. repens* when the experiment was initiated. Seven post-harvest treatments were randomised within four blocks resulting in 28 plots in total. Treatment details are provided in Table 1 and included different combinations of cultivation intensity, rhizome removal and cover crops. Treatment 2 was mouldboard ploughed to 22 cm depth after crop harvest and before using a *Vibro Flex* stubble cultivator (Kongskilde Industries A/S, Denmark) with goosefoot shares mounted on vibrating S-shaped tines cutting the soil over the full working width (illustrations and video clip on: http://www.kongskilde.com/Agriculture/Soil/Stubble%20Cultivation/Tined%20Cultivators/VIBRO%20FLEX%204000%204200%204300. Accessed 19 April 2013). Treatment 2 was included to compare treatments 3–7 with a stan-

Table 1 Treatments conducted in 2009 and 2010

Treatment	Date of treatment	No. of passes	Removal of rhizomes	Cover crop (CC)	Cultivation depth (cm)	Implement settings
1. Untreated	–	–	–	No		
2. Stubble cultivation	14, 21 August 2009 7, 14 September 2010	2	No	Yes	6 (first pass), 8 (second pass)	Forward speed 10 km h^{-1}
3. Rotary1(-CC)	21 August 2009 14 September 2010	1	No	No	20	Forward speed 5.2 km h^{-1}, 330 rotations min^{-1}
4. Rotary2(-CC)	21 August 2009 14 September 2010	2	Yes	No	20	Forward speed 5.2 km h^{-1}, 330 rotations min^{-1}
5. Rotary2(+CC)	21 August 2009 14 September 2010	2	Yes	Yes	20	Forward speed 5.2 km h^{-1}, 330 rotations min^{-1}
6. Rotary4(-CC)	21 August 2009 14 September 2010	4	Yes	No	20	Forward speed 5.2 km h^{-1}, 330 rotations min^{-1}
7. Rotary4(+CC)	21 August 2009 14 September 2010	4	Yes	Yes	20	Forward speed 5.2 km h^{-1}, 330 rotations min^{-1}

dard stubble cultivation practice. Treatments 3–7 were accomplished with a PTO-driven rotary cultivator, *Howard Rotalabour 600B-305S* (Kongskilde Industries A/S, Denmark), with slightly angled blades entering the soil vertically (illustrations and video clip on: http://www.kongskilde.com/Agriculture/Soil/PTO%20Harrows/Rotary%20Cultivator/HOWARD%20Rotavator%20%20Rotalabour%20500%20600%20700. Accessed 19 April 2013). *Rotalabour* was originally designed for soil preparation, but we modified the implement to uproot *E. repens* rhizomes. The roller at the rear of the machine was removed to allow for unhindered soil movement from the machine. We mounted winged shares at the front to furnish a full cut over the entire working width at 20 cm soil depth (see Appendix S1). Then, we increased the number of rotations from *c.* 200 rotations per minute (rpm) to 330 rpm. With these modifications, a large proportion of the loosened rhizomes was thrown into the air usually resulting in a complete exposure (see Appendixes S1 and S2). The exposed rhizomes were removed from the plots in treatments 4, 5, 6 and 7 after each pass using a PTO-driven rotary rake. Rhizomes were not removed in treatment 3 because we wanted to test the effect of just one uprooting without the extra work of rhizome removal. All passes (uprooting + removal) were made within the same day. A cover crop (CC) mixture of winter vetch (*Vicia villosa* Roth) (20 kg ha^{-1}), winter rye (*Secale cereale* L.) (40 kg ha^{-1}) and winter oilseed rape (*Brassica napus* L.) (0.75 kg ha^{-1}) was drilled in late August 2009 and early September 2010 after the last pass with the cultivators in treatments 2, 5 and 7. These treatments were then rolled (Appendix S2) after sowing the cover crop with the purpose of preserving soil moisture in the upper soil layer to promote seed germination. Gross plot size was 6 × 20 m of which the central 2.4 × 10 m was used for assessments of weed and crop growth. Spring barley (variety *Simba*) was grown in 2009, 2010 and 2011 at a target crop plant density of 350 plants m^{-2}: 178 kg ha^{-1} sown on 20 March 2009; 158 kg ha^{-1} sown on 29 March 2010; 176 kg ha^{-1} sown on 30 March 2011. The whole experimental area was mouldboard ploughed to 22 cm soil depth each year in March shortly before crop sowing. All plots were rolled right before and after ploughing using a concrete roller (936 kg per metre working width, diameter 900 mm) to compact the soil after ploughing and facilitate seedbed preparation. The final seedbed was completed with a powered harrow. Slurry was applied just before crop sowing using an amount corresponding to 70 kg total nitrogen ha^{-1} (*c.* 51 kg NH_4 ha^{-1}), 13–14 kg phosphorus ha^{-1} and 41–55 kg potassium ha^{-1} in both years. Manganese was applied in early May 2010 and 2011 using 1000 g ha^{-1}. Annual weeds were controlled in both years with a weed harrow with one pass pre-emergence and one post-emergence. All field operations were made in the longitudinal direction of the plots to avoid spreading of rhizomes from neighbouring plots.

Assessments

The amount of rhizome biomass that remained in the soil was recorded shortly after the tillage treatments on 21 August 2009 and 14 September 2010. Two 0.5 m^2 quadrats were randomly placed in each plot of treatments 1, 3, 4 and 6 (Table 1). All rhizomes within the quadrat and down to 20 cm soil depth were dug out and separated from the soil. The majority of rhizomes occurred in the 10–15 cm soil layer with no rhizomes seen at 20 cm depth (or further down, which was checked several times). These laborious excavations were limited to treatments 1, 3, 4 and 6, because it was assumed that treatments 5 and 7 would not deviate notably from treatments 4 and 6 owing to the consistency in treatments and the uniformity of the *E. repens* stand. Residual rhizomes following stubble cultivation in treatment 2 were not excavated either, since this treatment only served as a reference for the final effects recorded a year later.

Above-ground *E. repens* biomass production following the treatments in Table 1 was recorded in the subsequent year on 10 August 2010 and 9 August 2011, shortly before harvesting spring barley. Three 0.25 m^2 quadrats were randomly placed in each plot but at a separate location from where rhizomes had been excavated in the previous year. All above-ground plant material within the quadrat was cut at ground level. The plant material was separated into three fractions: crop, *E. repens* and other weeds, among which *Chenopodium album* L., *Galinsoga parviflora* Cav., *Spergula arvensis* L., *Viola tricolor* L., *Bilderdykia convolvulus* (L.) Dumort. and *Stellaria media* (L.) Vill. were the principal species. Dry matter of each fraction was obtained by drying the plant material in the oven for 24 h at 80°C.

Ground cover of the cover crop established in treatments 2, 5 and 7 (Table 1) was estimated from digital images taken *c.* 1 month after establishment on 21 September 2009 and 13 October 2010. Each image was taken of the whole 0.5 m^2 quadrat directly above the centre of the quadrat. Each image was subsequently analysed in Microsoft WORD by overlaying electronically a net consisting of 17 vertical and 17 horizontal lines. These lines created 289 intersections, and each intersection that visually on the computer screen was touched by living plant tissue was counted. Percentage plant coverage in the quadrat was then calculated by dividing the number of touched intersections with the total of 289 intersections. Coverage was estimated for vetch, rape and weeds separately and if possible also with a distinction between rye and *E. repens* shoots depending on the quality of the images. Counting intersections was considered to be a more objective method than visual scores of plant coverage (Melander *et al.*, 2009).

The level of soil compaction in the top 60 mm soil layer before growing spring barley in 2010 and 2011 was measured using a hand-held penetrometer with a flat, circular point (diameter 10 mm). The penetrometer measures the maximum force encountered when the point penetrates the soil to 60 mm soil depth. Fifteen penetrations were randomly made in each plot before and after seedbed preparation (rolling + ploughing + rolling + harrowing) and sowing.

Each plot was combined for barley grain yield in August 2010 and 2011 following the biomass cuts. Grain yields were adjusted to 85% dry matter content after grain samples had been dried in the oven for 24 h at 80°C.

Data analyses

Data were analysed using a general linear mixed model with normally distributed data (McCullagh & Nelder, 1989). Response variables were *E. repens* rhizome and shoot biomass, weed and crop shoot pre-harvest biomass, cover crop % vegetative cover, grain yield and soil penetration resistance. Fixed effects were the categorical variables SEASON (2009/2010 and 2010/2011, abbreviated to S0910 and S1011) and TREATMENT with blocks nested under SEASON and included as a random effect. Linear regression analysis was used to model *E. repens* rhizome vs. shoot biomass, soil penetration resistance before vs. after crop establishment and *E. repens* shoot biomass vs. crop grain yield. Non-linearity was checked by adding χ^2 to the linear model to test whether this model extension significantly improved the description of data (essentially testing a quadratic model vs. a linear model).

Except for the analyses on non-linearity and on regressions needing transformation, parameters of the linear models were estimated using residual likelihood estimations. Calculations were made with the MIXED procedure of SAS (SAS release 9.2), and means were calculated as least square means (LSM). Models were reduced by excluding non-significant effects based on likelihood ratio tests and Akaike's information criterion (Akaike, 1974). The denominator degrees of freedom (DDF) in *F*-tests and *t*-tests for mean separations were calculated according to Kenward and Roger (1997). In some cases, biomass data were log-transformed to obtain homogeneity of variance.

The SAS-procedure NLIN was used to estimate the parameters when analysing non-linearity and for the handling of transformation in regressions. Variances were stabilised using a transform-both-sides technique (Carroll & Ruppert, 1988). Parameter values in full models depended on the categorical variable SEASON. Block effects were nested under SEASON and assumed to affect all parameters in the model. Models were successively reduced on the basis of *F*-tests, leaving out non-significant effects at the 5% level.

Results

Rhizome biomass

The amount of rhizome biomass that remained in the soil following rotary cultivation declined markedly with each pass conducted (Table 2). For example, four passes resulted in *c*. 80% and 90% reductions in 2009 and 2010, respectively, as compared with the untreated. Rhizome biomass correlated linearly to above-ground shoot biomass in the subsequent year with no indications of any curvilinearity ($P = 0.4069$) within the range of data studied (Fig. 1). The simplest model had different slopes ($P < 0.0001$), no block effects ($P = 0.0701$) and one common intercept for both seasons ($P = 0.2597$) that did not deviate significantly from 0 ($P = 0.1314$).

Shoot biomass

Four passes with the rotary cultivator (treatments 6 and 7) produced the greatest *E. repens* shoot biomass reductions in the subsequent year 2010, while only minor differences were present among the treatments in 2011 (Table 2). Stubble cultivation followed by a cover crop (treatment 2) produced more *E. repens* control in S0910 than one pass with the rotary cultivator (treatment 3). No effects of cover crops on *E. repens* shoot biomass were detected when they were used following either 2 or 4 cultivations ($P = 0.2349$). The cover crop developed poorly in both seasons, only covering less than 10% of the soil surface in the autumn (data not shown).

Soil penetrometer resistance

Treatments that included a cover crop had higher levels of soil compaction than those that did not when measuring penetration resistance prior to crop establishment (Fig. 2). After crop establishment, penetration resistance reached a common value for both seasons and all treatments.

Barley biomass and yield

As with *E. repens* shoot biomass, crop biomass and yield were also not affected by the presence of a cover crop (Table 2). However, biomass of crop and other weeds were strongly affected by the amount of above-ground *E. repens* biomass in S0910 (Table 2). The

Table 2 Treatment means (untransformed, log-transformed and back-transformed) of *Elytrigia repens* rhizome biomass remaining in the soil after uprooting in seasons S0910 and S1011 respectively. Included are also *E. repens* shoot biomass, biomass of other weeds, crop biomass and grain yield following the treatments in the previous years

	Rhizome biomass (g m^{-2})		Shoot biomass (g m^{-2})			Other weed biomass (g m^{-2})	Crop biomass (g m^{-2})			
Seasons and treatments	Log-trf.	Back-trf.	Log-trf.	Back-trf.	Relative to untreated, %		Untrf.	Log-trf.	Back-trf.	Yield (t ha^{-1})
S0910										
1. Untreated	6.226 a	505.7	5.190 a	179.5		63.7 a		4.675 a	107.2	1.196 a
2. St.cult.(+CC)	–	–	4.336 b	76.4	−57	107.7 bce		5.736 b	309.8	2.165 b
3. R1(-CC)	6.163 a	474.9	4.968 a	143.7	−20	92.0 b		4.936 a	139.2	1.876 c
4. R2(-CC)	5.421 b	226.1	4.176 bc	65.1	−64	102.0 bc		5.580 b	265.1	2.165 b
5. R2(+CC)	–	–	4.071 bc	58.6	−67	120.7 ce		5.631 b	278.9	2.255 bd
6. R4(-CC)	4.579 c	97.4	3.727 ce	41.6	−77	84.0 ab		5.738 b	310.4	2.462 d
7. R4(+CC)	–	–	3.335 e	28.1	−84	129.4 e		5.662 b	287.7	2.594 d
SED	0.266		0.287			11.83		0.163		0.134
S1011										
1. Untreated	5.287 a	197.7	3.629 a	37.7		91.0 a	322.6 a			2.457 a
2. St.cult.(+CC)	–	–	1.482 bc	4.4	−88	76.1 a	379.2 a			2.544 a
3. R1(-CC)	4.323 b	75.4	1.930 b	6.9	−82	78.7 a	414.8 a			2.508 a
4. R2(-CC)	3.963 bc	52.6	1.637 bc	5.1	−87	76.9 a	356.1 a			2.268 a
5. R2(+CC)	–	–	1.647 bc	5.2	−86	102.1 a	400.7 a			2.259 a
6. R4(-CC)	3.258 c	26.0	0.479 bc	1.6	−96	66.9 a	383.0 a			2.325 a
7. R4(+CC)	–	–	0.155 c	1.2	−97	75.1 a	359.6 a			2.452 a
SED	0.396		0.851			15.43	44.23			0.179

SED is the maximum standard error of differences between means. Different letters alongside means in columns indicate significant differences at $P < 0.05$. A '-' means that no recordings were made.

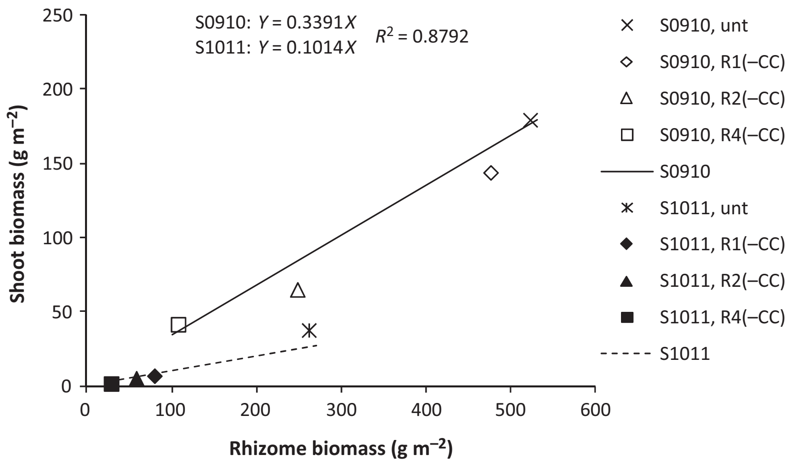

Fig. 1 Relationship between residual rhizome biomass in the soil after rotary cultivation and the amount of shoot biomass produced in the subsequent year shown for S0910 and S1011. Observed values are back-transformed means from analyses made on log-transformed data. Parameter values are from the simplest model obtained.

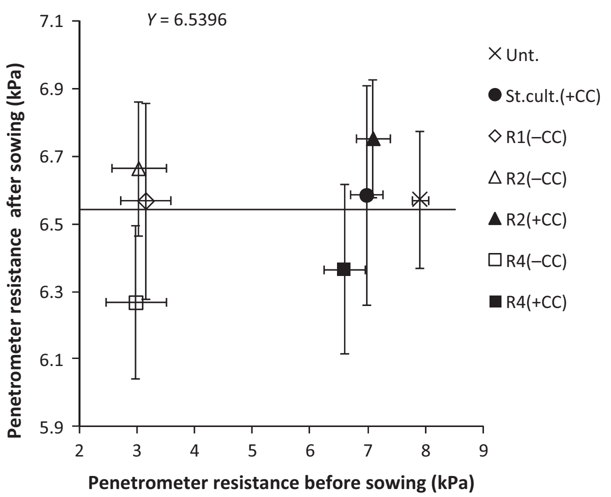

Fig. 2 Penetrometer resistance measured before and after crop establishment in spring shown for all seven treatments (Table 1) and averaging the two seasons S0910 and S1011. Horizontal bars are standard errors of the means of penetrometer resistance before crop sowing, and vertical bars are standard errors of the means of the resistance after crop sowing.

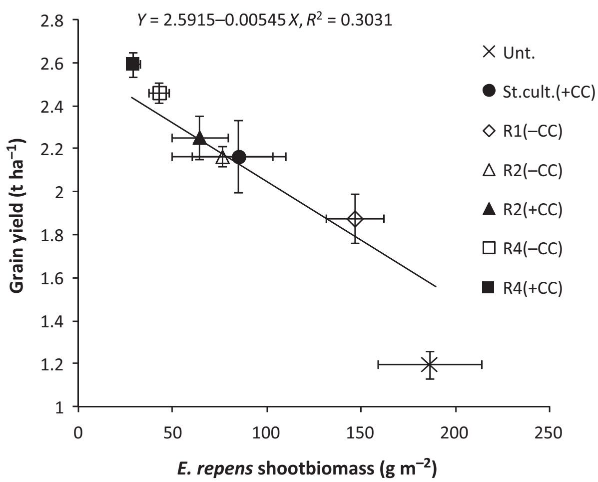

Fig. 3 The relationship between spring barley grain yield and the amount of above-ground *E. repens* biomass in S0910 following the seven treatments explained in Table 1. Horizontal bars are standard errors of the means of *E. repens* biomass, and vertical bars are standard errors of means of grain yield.

large amount of *E. repens* biomass associated with treatments 1 and 3 suppressed crop and weed growth markedly. In general, crop biomass was negatively correlated to *E. repens* biomass in S0910 (correlation coefficient $R = -0.7029$, $P < 0.001$), while the inverse relationship between other weeds and *E. repens* biomass was less pronounced ($R = -0.5947$, $P = 0.0008$). The negative impact of *E. repens* shoot biomass on crop growth resulted in reduced grain yield in S0910, with treatments 6 and 7 producing the greatest yields (Table 2). Crop yield responses could largely be explained by amounts of *E. repens* shoot biomass ($P < 0.001$) produced after tillage treatments (Fig. 3). The biomass of other weeds had an insignificant impact on crop biomass in S0910 ($P = 0.2233$). The amount of *E. repens* shoot biomass was generally much less in S1011, and treatment differences for *E. repens* shoot growth did not result in treatment differences for other weed biomass, crop biomass and grain yield (Table 2).

Discussion

As stated in hypothesis (a), residual rhizome biomass and shoot biomass the following year were proportionally related in both seasons. The relationship was linear, which suggests the absence of intraspecific competition among *E. repens* shoots at high shoot densities. The production of shoots per unit rhizome biomass remained constant over the range of residual rhizome biomass studied, even in August 2009 when rhizome density was very high (Fig. 1). This result contrasts other studies showing curvilinear relationships between initial shoot numbers in spring and shoot or rhizome biomass at crop harvest (Melander, 1995; Baziramakenga & Leroux, 1998). The lack of curvilinearity in our study may be due to low nutrient and water contents of the coarse sand (both factors were not measured). Rhizome density did not strongly influence shoot biomass, possibly because the crop was a better scavenger of limited resources than *E. repens*. The curve fitting in Fig. 1 included data from untreated and treatments 3, 4 and 6. In contrast to treatments 4 and 6, exposed rhizomes were not removed following treatment 3. Shoot growth might also have originated from the exposed fraction on the soil surface in treatment 3, in addition to the rhizomes left in the soil. If so, relatively more shoot growth would have been associated with treatment 3 than with treatments 4 and 6, where shoot growth only came from residual rhizomes in the soil. However, there were no indications that the exposed fraction had contributed to *E. repens* shoot growth after being ploughed under in early spring. Rhizome buds appeared unviable (not tested) after 7 months of exposure from the time of uprooting in the previous year till the following spring.

Traditional stubble cultivation (treatment 2) did not differ significantly from treatments involving one or two passes with the rotary cultivator in terms of *E. repens* shoot biomass reductions. And only in S0910 did four passes with rotary cultivation result in less shoot biomass than stubble cultivation. Control of *E. repens* is achieved through fragmentation of the rhizomes and by interrupting autumn shoot growth, both factors of possible importance in this study. Also, mouldboard ploughing before the establishment of a cover crop contributed to the overall effectiveness of treatment 2. Previous experiments with tine-based stubble cultivation strategies conducted over longer periods in the autumn for *E. repens* control on different soil types have demonstrated variable results, with effectiveness mostly in the range of 50–60% control (Permin, 1987). The strongest uprooting of rhizomes achieved with four passes of rotary cultivation in this study clearly points to the potential of developing machinery for uprooting and removal. One alternative to removal is destruction of the uprooted rhizomes that would allow nutrients embedded in the rhizomes to be recycled (Melander *et al.*, 2011).

Cover crop growing did not improve *E. repens* control or crop yield and hypothesis (b) could not be supported. The cover crop canopy developed poorly in both seasons, which can be partly attributed to the coarse sandy soil, which was nutrient-poor and had limited water-holding capacity. Moreover, post-harvest establishment of cover crops in mid-August or later in Northern Europe is rather late for cover crops to produce sufficient biomass between main crops, due to the short growing season (Melander *et al.*, 2013). Undersowing the cover crop in a main crop gives the cover crop a better start after crop harvest for subsequent growth. For example, undersowing red fescue in winter wheat can reduce late autumn biomass of *E. repens* rhizomes by 40% (Bergkvist *et al.*, 2010). Unfortunately, undersowing cover crops is incompatible with the concept of rapid post-harvest uprooting. Weed suppression by cover crops could be improved by identifying cover crop species with high competitive ability and investigating factors critical to cover crop establishment, such as planting timings, methods and spacing.

Hypothesis (c) was supported, as the level of soil compaction in the upper soil layer had reached the same level for all treatments including untreated when spring barley had been established. According to previous measurements on penetration resistance following concrete rolling on the same location, the level of soil compaction achieved in the upper soil layer can also be ascertained further down in the plough layer (Schjønning P., pers. comm., December 2012). The greater penetrometer resistance measured in the plots where a cover crop had been grown, but before establishing spring barley, was probably due to rolling and rooting from the cover crop that may have caused some compaction.

Rhizome uprooting and removal or destruction becomes especially important at high *E. repens* densities. For example, in 2010, vigorous *E. repens* shoot growth suppressed the growth of other plants. A linear relationship between barley grain yield and *E. repens* shoot biomass was also demonstrated by Melander (1995) for approximately the same shoot biomass range. Melander (1995) reported 16% yield loss per 100 g m^{-2} *E. repens* biomass, which is less than the 21% yield loss in this study. Since the 1995 study was conducted under conventional rather than organic practices, the yield potential was greater.

The intensive use of the type of machinery (rotary cultivator and rake) used in this study cannot be justified economically, not even at high *E. repens* infestations. According to the Danish Machine Pool Association (Kjeldal M, pers. comm. April 2013) and Nielsen *et al.* (1993), the costs for treatments 2 and 6 using implement sizes of relevance for practice would be *c.* €147 ha^{-1} and €427 ha^{-1}, respectively. The cost for treatment 2 includes labour, a 7-m-wide cultivator (work rate 0.24 h ha^{-1}) and a 4 furrows reversible plough (work rate 1.2 h ha^{-1}). For treatment 6, the cost covers labour and four passes with a 4-m-wide rotary cultivator (work rate 2 h ha^{-1}) and a 12-m-wide rake (work rate 0.22 h ha^{-1}). In comparison with treatment 1 (untreated), treatment 2 increased crop yield by 0.97 t ha^{-1} and treatment 6 by 1.27 t ha^{-1}. The net returns amount to €209 ha^{-1} for treatment 2 and €39 ha^{-1} for treatment 6 using a commodity price of €367 t^{-1} for organic barley grain (price level autumn 2012, https://www.landbrugsinfo.dk/oekologi/markedet-for-afgroeder/sider/Oekologiske_kornpriser.aspx. Accessed 7 June 2013). Evidently, the processes of uprooting and removal need to be combined into one implement that can accomplish the treatment in just one pass to minimise costs. Another drawback relates to potential soil structure damage, especially on more clayey soils with low organic matter contents. Intensive rotary cultivation reduces aggregate sizes and may cause slaking that eventually can result in crust formation on drying. Tilling crusty soils often creates large and strong aggregates with poor friability that deteriorates the seedbed quality (Young, 1992; Munkholm & Schjønning, 2004).

For the further development of implements for uprooting of rhizomes and other subsurface propagules, we suggest focusing on lifting principles, such as rolling webs for transporting objects from a pickup unit as known from harvesting potatoes (e.g. www.grimmeuk.com. Accessed 19 April 2013). Tests of this approach in Israel for the control of heavy *Cyperus rotundus* L. infestations have produced encouraging results. The reproductive tubers were uprooted and left exposed on the soil surface, where they experienced lethal desiccation during the hot summer period (Hershenhorn J, pers. comm. June 2012). A beach cleaner (www.beach-tech.com/en/products/beachtech.html. Accessed 19 April 2013) may also have potential for rhizome removal. In the preliminary testing mentioned in the introduction section, the beach cleaner was able to provide an almost complete removal of rhizomes in one pass, but only where the soil contained moderate rhizome biomass. The beach cleaner uses rolling webs, a pickup unit and a tank, all on the same implement, for the collection and removal of waste from sand beaches, but it needs modifications to become operational in a field situation. Work rates for lifting principles are relatively slow, but one pass should suffice for effective uprooting. This approach may become a cost-effective solution only if applied on highly infested patches or areas of the fields. And re-infestation with *E. repens* would probably happen more slowly than after traditional stubble cultivation where rhizome fragments are left on the field.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Colour plates: view from the rear of the *Rotalabour* machine and *Rotalabour* in action (also note the uniform stand of *Elytrigia repens*).

Appendix S2 Colour plates: rhizomes exposed on the soil surface after *Rotalabour* treatment and Rolling after catch crop sowing.