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RESEARCH ARTICLE

Root cutters: perennial weed control with a low risk of soil erosion and nutrient leaching

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Abstract

It is essential to reduce pesticide and tillage use in agricultural systems, but better alternatives for controlling perennial weeds are needed. The horizontal and vertical root cutters can fragment the roots and rhizomes of perennial weeds with minimal disturbance to the soil and vegetation cover. However, there is a lack of studies on how the root cutters affect multiple perennial weed species, and their effect on soil and nutrient losses. To fill this gap, three multi-year experiments in plowed systems were conducted in Norway and Sweden to study whether the roots cutters can control multiple perennial weed species as effectively as more intensive tillage methods (Experiments 1-2), without increasing soil and nutrient losses (Experiment 3). Overall, the more intensive tillage methods tested (rotary tiller, disc harrow, stubble harrow) did not provide significantly better perennial weed control than the horizontal root cutter. In Experiment 1, the horizontal root cutter reduced *Sonchus arvensis* and *Elymus repens* shoot biomass by 52% and 80%, respectively, compared to an untreated control. In Experiment 2, the horizontal root cutter reduced *Cirsium arvense* shoot numbers by 71% compared to the untreated control but failed to reduce *E. repens*. Horizontal root cutter treatment depth (7 vs. 15 cm) did not affect control efficacy. The horizontal root cutter treatment did not increase soil, water or nutrient losses compared to the untreated control, and resulted in 60% less soil and 52% less phosphorous losses than disc harrowing. Treatments with the vertical root cutter had 40% less *E. repens* and 22% less *S. arvensis* shoot biomass than treatments without the vertical root cutter. This manuscript is the first to show the true potential of the root cutters in plowed systems in northern Europe and their ability to control of multiple perennial weed species with low risk of soil and nutrient losses.

Keywords Conservation agriculture; Regenerative agriculture · Integrated pest management; *Elytrigia repens* · Organic agriculture

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1 Introduction

Weeds are the pest with the greatest potential to negatively affect crop quantity and quality, making effective weed management a prerequisite for sustainable agriculture (Oerke 2006). The most common and effective direct methods for managing weeds are herbicides and tillage, but there are strong incentives to reduce their use. For herbicides there are increasing concerns over the potentially negative effects on the environment, non-target organisms and human health (Van Bruggen et al. 2018). Moreover, the effectiveness of chemical weed control is in danger of eroding due to an ever-increasing number of herbicide resistant weeds and fewer available herbicides (Peterson et al. 2018). Tillage, on the other hand, has high energy and time requirements, and increases the risk of soil structure degradation, loss of organic carbon and soil microbial activity (Nunes et al. 2020a, b). Tillage can also increase the risk of nutrient losses and soil erosion (Klik and Rosner 2020). Therefore, sustainability concepts such as conservation agriculture, regenerative agriculture, organic farming and integrated weed management advocate a shift away from herbicides and/or tillage to more preventive measures such as cover crops, efficient crop rotations, precision fertilization (Nichols et al. 2015; Migliorini and Wezel 2017; Newton et al. 2020; Riemens et al. 2022).

A major obstacle for reducing pesticides and tillage is perennial weeds, such as *Elymus repens* (L.) Gould (couch grass), *Cirsium arvense* (L.) Scop. (creeping thistle) and *Sonchus arvensis* L. (perennial sow-thistle). Due to their underground storage and proliferation organs, such weeds are resistant to many forms of tillage and to herbicides that do not kill the belowground biomass (Ringselle et al. 2020; Soares et al. 2023). Perennial weeds often require intensive tillage in systems without herbicides (e.g., organic farming) and intensive use of herbicides, mainly glyphosate, in systems that reduce or exclude tillage (e.g., conservation agriculture) (Chauhan et al. 2012; Neve et al. 2024). There are some non-chemical alternatives to tillage that can destroy roots and rhizomes (e.g., steaming, electricity, solarization), but in general they are very energy demanding, slow and/or may not reach very deeply into the soil (Ringselle et al. 2020). Thus, there is a need for non-chemical tools that can effectively and resource-efficiently control perennial weeds with minimal soil disturbance and low risk of soil and nutrient losses.

In collaboration with researchers, the Kverneland Group have developed two root cutter prototypes that could potentially strike the golden balance between being able to fragment the roots and rhizomes of perennial weeds and causing only minimal soil disturbance. Unlike many other tillage implements (e.g. moldboard plough, disc cultivator and rotary tiller; see Skorupinski et al. 2024a), the root cutters do not invert or mix the soil, and cause minimal disturbance to the vegetation. An intact vegetation cover is important to prevent nutrient leaching, especially during wet autumns (Myrbeck et al. 2012). Thus, in theory the root cutters have a low risk of soil and nutrient losses. The first prototype, the vertical root cutter (VRC; see Figure 1A-B), cuts vertically through the soil using coulter disks and can reach 12 cm soil depth, meaning that it is likely to be most effective against species whose roots or rhizomes are typically found in the upper part of the soil profile, such as *E. repens* (Ringselle et al. 2018, 2023; Brandsæter et al. 2020). The second prototype, the horizontal root cutter (HRC), cuts horizontally using wide shears to a maximum depth of 30 cm (see Figure 1C-D). The working depth can be adjusted as desired, making it potentially effective against both perennial weed species with shallow and deep roots or rhizomes, such as *C. arvense* whose roots can reach more than a meter into the soil (Favrelière et al. 2020).

The VRC has been tested against *E. repens* in leys, showing that fragmenting its rhizome network once in a crisscross pattern can reduce *E. repens* rhizome biomass by 38%, while doing so twice can reduce it by 63% (Ringselle et al. 2018). This supported other results that have shown a large reductive effect of fragmenting the underground storage organs of perennial weed species (e.g., Boström et al. 2024; Skorupinski et al. 2024b). Moreover, the VRC treatment resulted in an increase in Italian ryegrass (*Lolium multiflorum* Lam.) and white clover (*Trifolium repens* L.), and the beneficial effect on Italian ryegrass was higher when it was performed in the growing crop compared to prior to crop sowing (170% vs 78%). Further experiments in an established ley have shown that the VRC does not operate well under hard soil conditions (Ringselle et al. 2023). The HRC has been shown to be able to reduce *C. arvense* shoot numbers, patch expansion and root carbohydrate content (Weigel and Gerowitt 2022; Weigel et al. 2023). When combined with cover crops, the HRC has had a comparable effect as moldboard plowing on *C. arvense* and *E. repens* (Weigel et al. 2023, 2024).

So far, no studies have been published that demonstrate the efficacy of the root cutters in controlling multiple perennial weed species with different root or rhizome traits, nor how the root cutters affect soil erosion or nutrient leaching. The current study will fill these gaps by presenting the results from a series of experiments from Norway and Sweden. The tested hypotheses were: 1) the HRC can provide effective control of multiple perennial weed species that is comparable to more intensive tillage methods, 2) the VRC increases the efficacy of other tillage methods against perennial weeds, 3) shallow tillage treatments are more effective against perennial weeds with shallowly growing roots/rhizomes (e.g. *E. repens*, *S. arvensis*) and deeper tillage is more effective against those with deep roots/rhizomes (e.g. *C. arvense*) and 4) the HRC causes less soil erosion and nutrient leaching than disc harrowing.

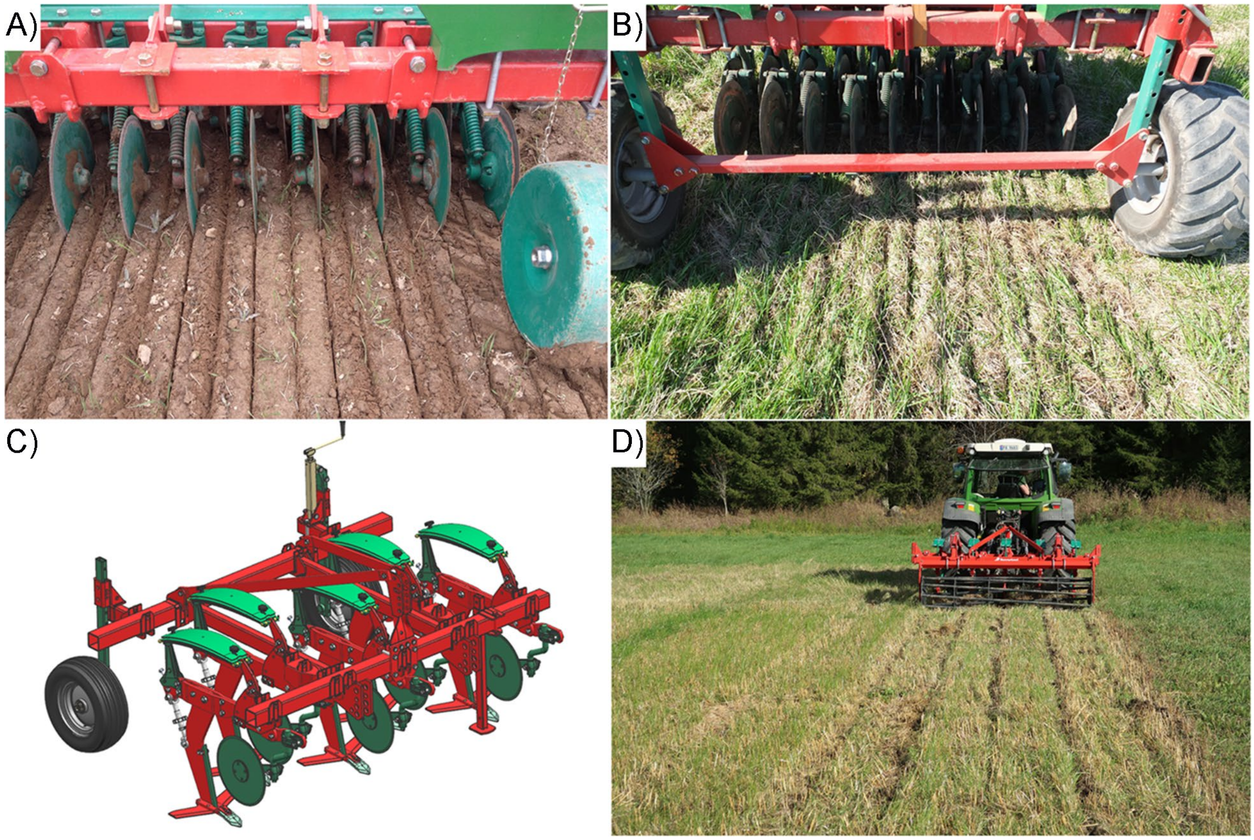

Fig. 1 The vertical root/rhizome cutter (VRC) used in soil and (**A**) and in a growing crop (**B**); and the horizontal root/rhizome cutter (HRC) as schematic (**C**) and working in the field (**D**). The soil disturbance from both VRC and HRC is minimal compared to conventional tillage, in particular compared to moldboard plowing and rotary tilling. Photocredit: Göran Bergkvist (**A** & **B**), Kverneland Group AS (**C**), Lars Olav Brandsæter (**D**).

2 Materials and methods

Three multi-year experiments were conducted to test the hypotheses. An overview of the location of the three experiments and their treatments is shown in supplementary Figure S1.

2.1 Experiment 1 and 2

2.1.1 Study sites, experimental design and treatments

The purpose of Experiment 1 was to study if the HRC can provide as effective control of multiple perennial weed species as more intensive tillage treatments, and if the VRC could further increase the control efficacy. Experiment 1 was performed in Ås, Norway (59°40′N 10°46′E) from 2016 - 2019. The soil at the Ås site is a silty clay loam with poor natural drainage and classified as an epistagnic albeluvisol (siltic), according to the WRB system (World Reference Base 2006). The site had naturally established populations of *E. repens, S. arvensis, C. arvense, Stachys palustris* L. (marsh woundwort) and *Vicia cracca* L. (tufted vetch) that dominated the weed flora. There were no prominent annual weeds. All plots were fertilized with dried chicken manure ["Marihøne Pluss" 8 (%N) – 4 (%P) – 5 (%K)] corresponding to 80–100 kg total N ha^{-1}. The fields were sown with spring barley (*Hordeum vulgare* L.) in 2016 and 2017, and oat *(Avena sativa* L.) in 2018 and 2019 (Table 1). Weather data for the site of Experiment 1 and 3 is given in Table 2.

The purpose of Experiment 2 was to study if the HRC can provide as effective control of multiple perennial weed species as more intensive tillage treatments. Experiment 2 was performed at Ultuna close to Uppsala, Sweden (59°48′N, 17°39′E) from 2017–2019. The soil at the Ultuna site is a heavy clay soil, and classified as a vertisol, according to the WRB system (World Reference Base 2006). The site had naturally established populations of *C. arvense* and *E. repens*. Only *Chenopodium album* L. (lamb's quarters) was a prominent annual weed. Mineral fertilization was applied each year at sowing as NP 27-3 with a N-supply of 80 kg ha^{-1}. The fields were sown with spring barley (*Hordeum vulgare* L.) in all experimental years. Weather data for the site of Experiment 2 are given in Table 3.

Table 1 Dates for management and treatments in Experiment 1, 2 and 3. VRC = vertical root/rhizome cutter, HRC = Horizontal root/rhizome cutter. A second stubble treatment was performed if the perennial weeds had had sufficient time to reach their compensation stage and the soil conditions allowed for tillage (e.g. not too wet, as was the case in Experiment 2 in 2017). Experiment 1 was sown with spring barley in 2016 (cv. "Thule" 210 kg/ha) and 2017 (cv. "Brage" 200 kg/ha) and oats in 2018 (cv. "Niklas" 220 kg/ha) and 2019 (cv. "Niklas" 230 - 240 kg/ha). Experiment 2 was sown with spring barley 200 kg/ha, and Experiment 3 with spring oat 210 kg/ha, in all years.

Experiment	Operation	2016	2017	2018	2019
1	Spring plowing, all plots	11 May	26 May	22 May	23 Apr
	Establishment (leveling, fertilizing, seedbed preparation, rolling, sowing), all plots	12 May	27 May	22 May	24–25 Apr
	Threshing, all plots	27 Aug	20 Sep	26 Aug	2 Sep
	Main registration – Weeds	24–31 Aug	21–28 Sep	27 Aug-3 Sep	9–13 Sep
	First stubble treatment (HRC, VRC, disc harrow, stubble harrow, rotary tiller, mowing)	7 Sep	28–29 Sep	6–7 Sep	
	Second stubble treatment (HRC, VRC, disc harrow, stubble harrow, rotary tiller, mowing)	26–27 Sep	Not applied	Not applied	
2	Establishment (leveling, fertilizing, seedbed preparation, rolling, sowing), all plots		13 May	13 May	2 May
	Main registration - Weed shoots		14–16 Aug	2–3 Jul	8–9 Aug
	Main registration - Grain/weed biomass/2nd weed shoots		1–2 Sep	21–28 Aug	1 Sep
	Threshing, all plots		18 Sep	1 Sep	
	First stubble treatment (HRC, disc harrow, stubble harrow)		4 Oct	3 Sep	
	Second stubble treatment (HRC, disc harrow, stubble harrow)		Not applied	26–27 Sep	
	Autumn plowing, all plots	15 Oct	24 Oct	16 Oct	
3	Spring plowing, all plots	25 Apr	23 May	30 Apr	
	Establishment (fertilizing, seedbed preparation, rolling, sowing), all plots	10 May	24 May	11 May	
	Threshing, all plots	28 Sep	25 Sep	21 Sep	
	Stubble treatment (HRC, disc harrow)	25 Oct	20 Sep	28 Sep	

Both Experiment 1 and 2 used complete randomized block designs with 4 blocks. Experiment 1 used 2 x 14 m plots, while Experiment 2 used 6 x 7 m plots. In Experiment 1, there were 2-meter margins between all plots, which were stubble-harrowed in the autumn to control weeds. Prior to the experiments, both sites had been organically farmed for many years with small-grain cereals dominating the rotation. Levelling, fertilizing,

Table 2 Records of monthly precipitation, temperature [taken from NMBU weather station SN17850 (NCCS 2023)] and radiation [taken from weather station Ås (LMT 2023)] for 2016–2019 in Ås, Norway, where both Experiment 1 and 3 took place. Means are for the period 1991–2020.

	Mean temperature (°C)					Radiation ($\sum$ MJ m^{-2})					Precipitation ($\sum$ mm)				
	2016	2017	2018	2019	Mean	2016	2017	2018	2019	Mean	2016	2017	2018	2019	Mean
Jan	−6.8	−1.4	−2.3	−4.2	−2.8	32	32	27	37	33	59	61	88	26	66
Feb	−1.3	−1.9	−4.7	0.2	−2.5	104	94	94	78	95	78	63	57	97	50
Mar	2.1	2.1	−3.5	1.8	0.6	190	201	241	220	224	57	43	23	84	45
Apr	5.5	4.6	5.2	7.7	5.4	313	359	375	434	356	69	44	30	19	50
May	11.8	11.1	15.1	9.7	10.7	496	391	595	455	490	72	67	34	111	62
Jun	15.9	14.5	17.0	14.5	14.5	565	512	640	474	553	80	95	86	126	77
Jul	16.4	16.1	20.5	17.0	16.7	512	530	621	541	509	69	41	29	52	82
Aug	14.8	14.6	15.5	16.2	15.7	378	399	380	367	394	135	133	55	101	96
Sep	14.3	11.6	12.2	11.0	11.5	265	179	252	222	251	37	122	129	184	90
Oct	5.4	6.7	6.8	5.0	6.1	102	118	123	107	110	25	139	44	128	105
Nov	0.5	1.3	3.0	0.2	1.8	40	51	29	32	39	79	101	134	134	99
Dec	0.7	−2.0	−1.8	0.0	−2.0	19	21	19	19	19	26	66	85	71	72

Table 3 Records of monthly precipitation, temperature, and radiation for 2017–2019 at Ultuna, Sweden, where Experiment 2 was conducted, compared with means for the period 1991–2020 (Anonymous 2019; SMHI 2023). Means are for the period 1991–2020.

	Mean temperature (°C)				Radiation ($\sum$ MJ m^{-2})				Precipitation ($\sum$ mm)			
	2017	2018	2019	Mean	2017	2018	2019	Mean	2017	2018	2019	Mean
May	10.5	15.4	10.2	10.7	741	746	540	586	17	8	54	38
June	14.7	16.4	17.6	14.9	703	671	678	616	53	9	24	58
July	16.5	21.7	16.6	17.6	716	703	604	607	32	78	55	59
Aug	15.9	17.9	17.1	16.4	469	486	494	473	32	64	61	67
Sept	12.2	12.9	11.9	11.8	233	301	302	290	41	37	37	48
Oct	6.9	7.5	6.1	6.4	122	149	124	133	57	20	68	52

seedbed preparation, sowing and rolling were common for all experimental plots in both experiments. Additionally, spring plowing was used in all experimental plots in Experiment 1, and autumn plowing in Experiment 2 (Table 1), as this is common practice in Norway and Sweden, respectively.

The following five treatments were performed in both Experiment 1 and 2: 1) Untreated control, 2) Disc harrow 12 cm depth, 3) Stubble harrow 12 cm depth, 4) HRC 7 cm depth, and 5) HRC 15 cm depth. In Experiment 1 an additional five treatments were performed: 6) Mowing, 7) Mowing + VRC 12 cm depth, 8) HRC 12 cm depth + VRC 12 cm depth, 9) Disc harrow 12 cm depth + VRC 12 cm depth, and 10) Rotary tiller with vertical movement 12 cm depth. Implement specifications for the treatments are provided in Table 4. In both the HRC + VRC and Disc harrow + VRC treatments, the VRC was performed after the other tillage treatment. Timing of the treatments are given in Table 1. A second stubble treatment was performed if the perennial weeds had had sufficient time to reach their compensation stage (Ringselle et al. 2021) after the threshing and the soil conditions allowed for tillage (e.g., not too wet).

2.1.2 Assessment

Assessments were done in the autumn for both Experiment 1 and 2 (Table 1). Experiment 1 was assessed using four 0.5 m^2 (thus, 2 m^2 in total per plot) randomly placed quadrants for all measurements. In the quadrants all shoots were counted and all perennial shoot biomass collected. The biomass samples were dried at 70 °C for 72 h to determine the dry weight. An experimental combine harvested 1.5 m x 7 m in the middle of each plot. The grain yield of the plots was weighed at harvest and dried for storage. Grain moisture at harvest, grain weight per hectoliter and screening percentage were determined. Final grain yield was adjusted to 85% dry matter.

In Experiment 2 shoot numbers were assessed using four 1 m^2 randomly placed quadrants (4 m^2 total per plot) for *E. repens*, while *C. arvense* and *C. album* shoots were counted across the middle of the whole plot in a two-meter-wide strip (i.e., 14 m^2). For shoot biomass four subplots with an area of 0.25 m^2 were randomly selected in each plot (thus, 1 m^2 in total per plot). All plant material was harvested, and separated into spring barley, *C. arvense*, *E. repens*, *C. album* and other weeds. The plant material was dried at 105˚C until constant weight was achieved, and dry weight was recorded. Before drying, spring barley plants were

Table 4 Details of the machines and implements used in Experiments 1–3.

Experiment	Model name	Tilling implement	PTO (rpm)	Forward Speed (km $^{h-1}$)
1–3	Kverneland Horizontal Root/Rhizome Cutter (HRC) (prototype) (2.5 m)	54 cm wide flat shares like a goosefoot share, cuts the roots/rhizomes to an even depth throughout the whole width.	-	7
1	Kverneland Vertical Root/Rhizome Cutter (VRC) (prototype) 1.5 m)	The 36 cm diameter discs make cuts 10 cm apart.	-	5
1	Rotary tiller	Howard L-tine Cultivator. Vertically aligned PTO-driven L-tines	1000	5
1	Kverneland FH 180 Chopper	Stubble and pasture mower.	540	5–7
1 & 3	Kverneland Disc Harrow	Disc diameter 35 cm. Kverneland, Norway.	-	5–6
2	Stubble Harrow	Goosefoot shares	-	5–6
2	Väderstad Carrier disc cultivator (4.25 m)	Disc diameter 45 cm.	-	
2	Väderstad Swift Cultivator (4 m)	Goosefoot shares, width 24 cm	-	

separated into ears and straws. After drying, twenty ears from each plot were separated into kernels and remains in order to estimate the grain yield production. The ears consisted of about 82% grains and the grain yield (15 % water content) was estimated as grain yield = (0.82 × ear weight) × 1.15. All data were calculated to density (shoots m^{-2}) and aboveground dry matter (DM) (g m^{-2}) before statistical analysis.

2.2 Experiment 3

2.2.1 Study site, experimental design and treatments

The objective of Experiment 3 was to assess the soil and nutrient losses of using the HRC compared to disc harrowing and an untreated control. Experiment 3 was performed from 2016-2019 in Ås, Norway (59° 39' 08.26 N 10° 50' 12.58 E, altitude 96 m) at an experimental site established by Njøs and Hove (1986). The site is located not far from the site of Experiment 1. The soil is a silty clay loam with 27% clay, 62% silt, 11% sand and 2.4% organic matter, and is described as an albeluvisol according to the WRB system (World Reference Base 2006). The area has been land levelled and the slope is 13%.

Experiment 3 used a complete randomized block design with three blocks and plots measuring 21 x 8 m. The site had been growing small-grain cereals prior to experiments. Spring plowing, spring harrowing, levelling, fertilizing, seedbed preparation, cereal sowing and rolling were common for all experimental plots. Straw was left on the soil surface after harvest. The treatments were: 1) Untreated control, 2) Disc harrow 10 cm depth and 3), HRC 15 cm depth. Management dates can be found in Table 1, weather data in Table 3 and details on the treatment machinery in Table 4.

2.2.2 Assessment

The surface runoff [soil, phosphorous (P), phosphates (PO4_P) and nitrogen (N)] was collected by a pipe system and the runoff was measured by tilting bucket. The number of tilts is recorded by a mechanical counter. Water sampling was volume proportional by storing a small volume of water from every second tilt in a plastic container. Soil particles in water samples was analyzed as suspended material with filtration through fiberglass filters (NS-EN 872, 2005). P and PO4_P were analyzed with a spectrophotometric method with ammonium molybdate (NS-EN ISO 6878, 2004). N was analyzed after oxidation with peroxydisulfate (NS 4743, 1993). There were two containers for every plot so that both small runoff episodes (1–2 mm of runoff), and larger episodes (up to 50 mm of runoff) could be sampled. In our study surface runoff was measured from tillage operation in autumn to plowing in spring in the three experimental periods (2016-2017, 2017-2018, 2018-2019). Precipitation was recorded manually for the three experimental periods and was 312 mm in 2016-2017, 460 mm in 2017-2018 and 483 mm in 2018-2019.

2.3 Statistical analyses

The three experiments are randomized complete block designs. Experiment 1 and 2 used four blocks and Experiment 3 used three blocks. The same plots within the blocks were observed in each of the years. In Experiment 1 transformed response variables were used in the analyses concerning weed number and weed biomass, to achieve approximate normality and equal variance. The transformation used was ln(y + 1) where y is the original response variable and ln(•) is the natural logarithm function. For yield no transformation was used. In Experiment 2 and 3 the original response variables were used in the analyses without any transformation. All response variables were modelled using mixed linear models. For most response variables treatment and year were fixed factors, and significant interactions were also included in the model. The exception was the response variables *E. repens* and *C. arvense* number in Experiment 2 where time, with four levels, was used instead of year because there were two observation times in both 2018 and 2019. Several potential covariates were used, and depending on their significance the final models contain different covariates, in some situations no covariates. In all the models block was a random factor. To take into account that observations from the same plot can be correlated, an AR(1) covariance structure was used, except for the sum of *E. repens* and *C. arvense* biomass in Experiment 2 where a compound-symmetry covariance structure was used. To compare and order the least squares means of the levels of fixed effects Tukey-Kramer's multiple comparison method was used. The calculations were done using proc glimmix in SAS 9.4 (Sas Institute Inc., Cary. NC. USA.).

In these analyses linear mixed models were used, which can typically be expressed as:

$$y_{ijkl} = m + a_i + b_j + B_k + g \cdot x_{ijkl} + e_{ijkl}$$

In this model y_{ijkl} is the observed or transformed response variable for treatment i, in year j, in block k, and plot l. The plots have different numbers in the different blocks. m is a general mean, a_i and b_j are the main and fixed effects of treatment i and year j, respectively. B_k is the random effect of block k, assumed to be normally distributed random variable with expected value 0 and variance ${s_B}^2$. x_{ijkl} is the value of the covariate (if used) corresponding to y_{ijkl}. A linear relationship between x_{ijkl} and y_{ijkl} is assumed, where g is the slope. The e_{ijkl} is the error term assumed to be normally distributed random variable with expected value 0 and variance s^2. All B_k's are assumed to be independent and independent of the e_{ijkl}'s. The e_{ijkl}'s from the same plot (in the different years) are assumed to have an AR(1) covariance structure or, in some cases, a compound symmetry structure. All parameters with unknown values are estimated using the data. For some response variables interactions between the treatments and years (when clearly significant) are also included in the model. For some response variables more than one covariate were used. The covariate(s) are typically weed number or weed biomass in the plots the year before the treatments were applied. The covariates were used to correct for their possible influence on the observations in the experimental years since the number and biomass of existing perennial weeds at the start of the experiment can be expected to strongly affect perennial weed abundance during the consequent experimental years. Year in the model is an expression of the number of years from the start of the experiment.

P-values are presented in Tables 5-7.

3 Results and discussion

3.1 Initial perennial weed abundance and yearly variation

There was a medium-high initial perennial weed pressure in Experiment 1 and 2. In the pre-treatment sampling, there were on average 160 *E. repens* and 168 *S. arvensis* shoots m^{-2} in Experiment 1, and 108 *E. repens*, 5.4 *C. arvense* and 7.1 *C. album* plants m^{-2} in Experiment 2. *Stachys palustris*, *V. cracca* and *C. arvense* in Experiment 1 were not counted pre-treatment. The purpose of Experiment 3 was to assess nutrient and soil leaching due to tillage, so weed assessments were not conducted.

There was a great deal of yearly variation within the data, but almost no interactions between year and treatment (Tables 5-7). One major factor for the yearly variation was the 2018 summer drought, which resulted in a much lower cereal yield (1983 vs. 3005 kg/ha) in 2018 than 2019 in Experiment 2, but not Experiment 1, and resulted in a lower perennial weed biomass for all species in both Experiment 1 and 2, except *C. arvense*. Perennial weed shoot numbers were not likewise affected by the 2018 drought, instead the pattern varied depending on species, for example in Experiment 1 the number of *S. arvensis* shoots increased on average each year, while *E. repens* had on average significantly more shoots in 2017 than in 2018 and 2019.

In Experiment 3, the surface runoff, soil erosion and P leaching were all greatest in the 2017-2018 period, for example 862 kg ha^{-1} soil was lost on average in 2017-2018 compared to 369 kg ha^{-1} in 2016-2017 and 135 kg ha^{-1} in 2018-2019. Yet 2018-2019 was the period with the highest precipitation.

3.2 Effect of HRC treatments on crop yield and perennial weed abundance

There was support for Hypothesis 1, which stated that the HRC can provide effective control of multiple perennial weed species that is comparable to more intensive tillage methods (i.e., disc harrow, stubble harrow, rotary tiller). In Experiment 1, the HRC treatments increased the cereal yield by 26–28% (Figure 2A; Table 5) and reduced total perennial weed biomass by 46–51% (Figure 3C; Table 6), compared to the untreated control. In comparison, mowing and stubble harrowing both failed to increase cereal yield or reduce total perennial weed biomass, while the disc harrow had a similar effect to HRC (+30% cereal yield and −51% total perennial weed biomass). The rotary tiller had the best effect (+40 cereal yield and −67% total perennial weed biomass) but not significantly better than the HRC. No treatment had a significant effect on cereal yield (Figure 2B; Table 5) or total perennial weed biomass (Table 6) in Experiment 2.

On a species level, none of the more intensive tillage methods or mowing provided better control of *E. repens*,

Table 5 ANOVA-table of the effects of treatment and year on crop yield in Experiment 1 and 2, and surface runoff, soil loss, phosphorous (P), phosphate (PO4_P) and nitrogen (N) leaching in Experiment 3. Initial number (No) of *Elymus repens* shoots was used as a covariate for crop yield when it was significant. LN = natural logarithm.

	Experiment 1	Experiment 2	Experiment 3				
	Crop yield (kg ha^{-1})	Crop yield (kg ha^{-1})	Surface runoff (mm)	Soil loss (kg ha^{-1})	P loss (kg ha^{-1})	PO4_P (kg ha^{-1})	Total N (kg ha^{-1})
Treatment	**<.0001**	0.3	0.5	**0.04**	0.06	0.7	0.2
Year	**<.0001**	**<.0001**	**0.0002**	**0.0002**	**<.0001**	**0.01**	0.9
Year*Treatment	1	0.3	1	0.5	0.3	0.3	1
ElymusNo	**0.01**	**0.005**					
Transformation				LN	LN	LN	LN

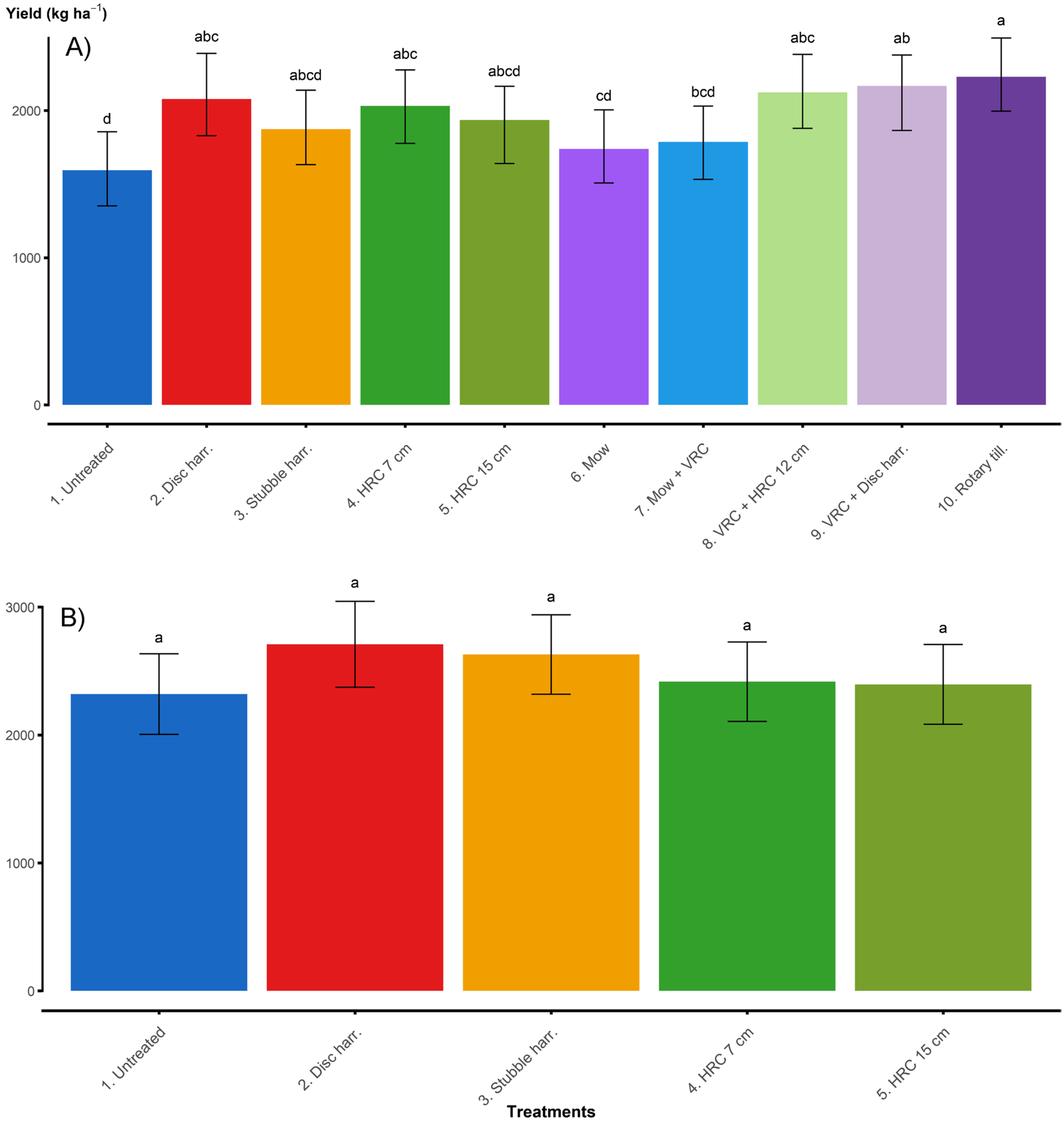

Fig. 2 Results of different treatments on crop yield in **A**) Experiment 1 in Norway, averaged over the sampling years 2017-2019; and **B**) Experiment 2 in Sweden, average over the sampling years 2018-2019. All treatments were plowed in spring each year in Experiment 1, and in autumn in Experiment 2. VRC = vertical root/rhizome cutter, HRC = Horizontal root/rhizome cutter. Letters show the result of Tukey test at α =0.05.

S. arvensis, C. arvense, S. palustris or *V. cracca* than the HRC – except in one case. In Experiment 2, the disc harrow reduced the number of *E. repens* shoot numbers by 75% compared to the untreated control, an effect that was also significantly better than the HRC treatments (Figure 4E; Table 7). However, while the HRC failed to control *E. repens* in Experiment 2, the HRC at 7 cm depth reduced the number of *C. arvense* shoots by 71% (Figure 4D; Table 7), which the disc harrow failed to do. Moreover, in Experiment 1 the HRC at 7 cm depth reduced

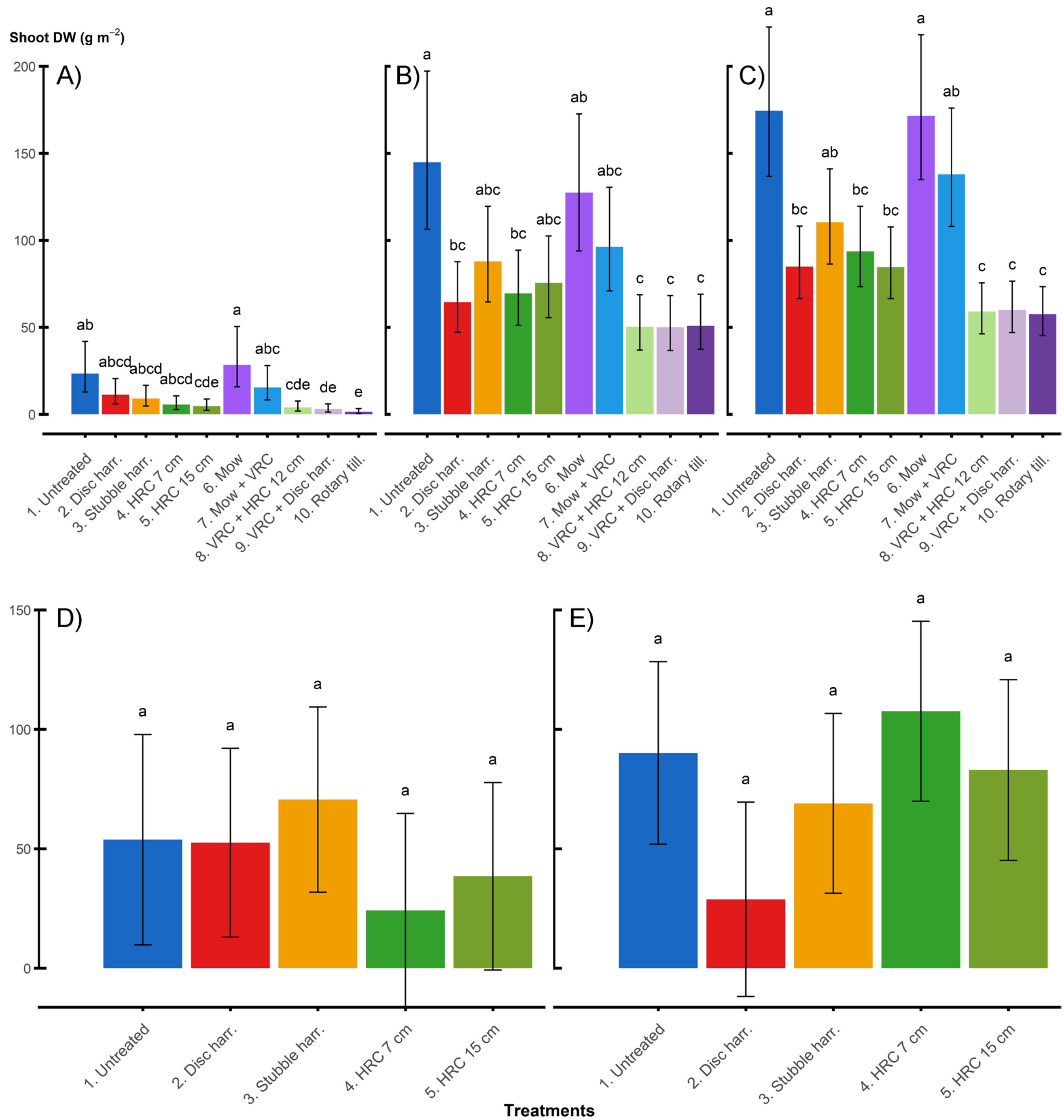

Fig. 3 Results from Experiment 1 in Norway on the effect of different treatments on the aboveground shoot dry weight (DW) biomass of **A**) *E. repens*, **B**) *S. arvensis* and **C**) the combined shoot biomass of all five perennial weed species present at the site (*E. repens*, *S. arvensis*, *S. palustris*, *V. cracca*, *C. arvense*), averaged over the sampling years 2017-2019; and Experiment 2 in Sweden on the effect of different treatments on the shoot DW biomass of **D**) *C. arvense* and **E**) *E. repens*, average over the sampling years 2018-2019. All treatments were plowed in spring each year in Experiment 1, and in autumn in Experiment 2. VRC = vertical root/rhizome cutter, HRC = Horizontal root/rhizome cutter. Letters show the result of Tukey test at α =0.05.

S. arvensis biomass by 52% (Figure 3B) and the 15 cm treatment reduced *E. repens* biomass by 80% compared to the untreated control (Figure 3A; Table 6). Furthermore, a contrast between the two HRC treatments and the untreated control showed that the HRC significantly reduced both *E. repens* (−71%; *p*-value=0.01) and *S. arvensis* (−26%; *p*-value=0.004) shoot numbers. No treatment significantly reduced *V. cracca* or *S. palustris* in Experiment

Table 6 ANOVA-table of the effects of treatment and year on the shoot biomass of *Elymus repens*, *Sonchus arvensis*, *Stachys palustris*, *Vicia cracca* and the total perennial weed shoot biomass (all four species plus *C. arvense*) in Experiment 1, and on the shoot biomass of *E. repens*, *C. arvense* and the total perennial weed shoot biomass in Experiment 2. Different covariates of initial dry weight (DW) or shoot numbers (No) of different perennial weed species were used depending on whether they had a significant effect. LN = natural logarithm.

	Experiment 1 – shoot biomass					Experiment 2 – shoot biomass		
	Elymus repens	*Sonchus arvensis*	*Stachys palustris*	*Vicia cracca*	Total per. weed biomass	*Elymus repens*	*Cirsium arvense*	Total per. weed biomass
Treatment	**<.0001**	**<.0001**	0.2	0.2	**<.0001**	0.09	0.5	0.6
Year	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.2	**0.003**
Year*Treatment			**0.04**	0.1		0.3	0.3	0.1
ElymusDW	**0.0002**				**0.04**			
SonchusNo		**0.001**			**0.009**			
ElymusNo						**0.0002**		**0.04**
CirsiumNo							0.1	
Transformation	LN+1	LN+1	LN+1	LN+1	LN+1			

1 compared to the untreated control (Tables 6-7). For *V. cracca* this may be explained by relatively patchy occurrence of *V. cracca* in the field compared to *E. repens* and *S. arvensis*. *Stachys palustris* appears to have increased in most treatments that suppressed *E. repens* and *S. arvensis* – albeit only significantly for the rotary tiller, which had a higher number of shoots than the mowed treatment (9.1 vs. 2.3 plants/m^2, respectively; Figure 4C; Table 7). There are not many studies on *S. palustris*, but it has sometimes been reported as being especially tolerant of tillage (e.g. Korsmo 1954). In combination with the decrease in its competitors, this could explain its increase in the tilled treatments that reduced *E. repens* and *S. arvensis*.

It is not uncommon that herbicides or tillage fails to control weeds in one year and succeeds in another (see e.g., Lötjönen and Salonen 2016). One reason that the HRC succeeded in controlling *E. repens* in Experiment 1 and failed in Experiment 2 could be because autumn plowing was used in Experiment 2 and spring plowing in Experiment 1. Plowing so soon after the HRC treatment may have reduced the impact of the HRC treatment in Experiment 2. A not yet published experiment testing different combinations of HRC and plowing at different depths showed that using both HRC and plowing at the same depth had no additive effects on *C. arvense*, most likely because the effect was too similar (Brandsæter pers. communication). Previous studies have shown that plowing time has a relatively minor importance on *E. repens*, while spring plowing is more effective than autumn plowing on *C. arvense* and *S. arvensis* (Brandsæter et al. 2017). However, this was only investigated with or without disc harrowing, so it is possible that the HRC followed by autumn plowing is less effective against *E. repens* than when combined with spring plowing. Despite the failure to control *E. repens* in Experiment 2, however, the HRC showed that it can have a strong reductive effect on *E. repens*, *S. arvensis* and *C. arvense*, supporting other studies that fragmenting the roots/rhizomes of perennial weeds has a negative effect on their growth and propagation (e.g., Skorupinski et al. 2024b, a). One limitation of this study is that it only studied the aboveground biomass, which may differ significantly from the effect on the belowground biomass (cf. Ringselle et al. 2015), but this is primarily a problem in one-year studies. So, the 2–3 year duration of the experiments compensates for this limitation.

3.3 Effect of VRC treatments on crop yield and perennial weed abundance

There was support for Hypothesis 2, which stated that the VRC increases the efficacy of other tillage methods against perennial weeds. HRC+VRC and disc harrow+VRC reduced total perennial weed biomass by 66% (Figure 3C) and increased cereal yields by 33 and 36% (Figure 2A), respectively, compared to the untreated control. Thus, the HRC+VRC and disc harrow+VRC had a similar effect as the most effective and most intensive tillage method, the rotary tiller (−67% total perennial weed biomass and +40% cereal yield). This was also true at the species level. The disc harrow+VCR, HRC+VRC and rotary tiller treatments all reduced *S. arvensis* shoot biomass by 65% and shoot numbers by 45–46%, compared to the untreated control (Figure 3B and 4B; Tables 6-8). For *E. repens*, the rotary tiller had a slight advantage, reducing *E. repens* shoot biomass by 94% and shoot numbers by 88%. In comparison the disc harrow+VRC and VRC + HRC treatments reduced *E. repens* shoot biomass by 87 and 83%, respectively; and they did not quite significantly reduce *E. repens*

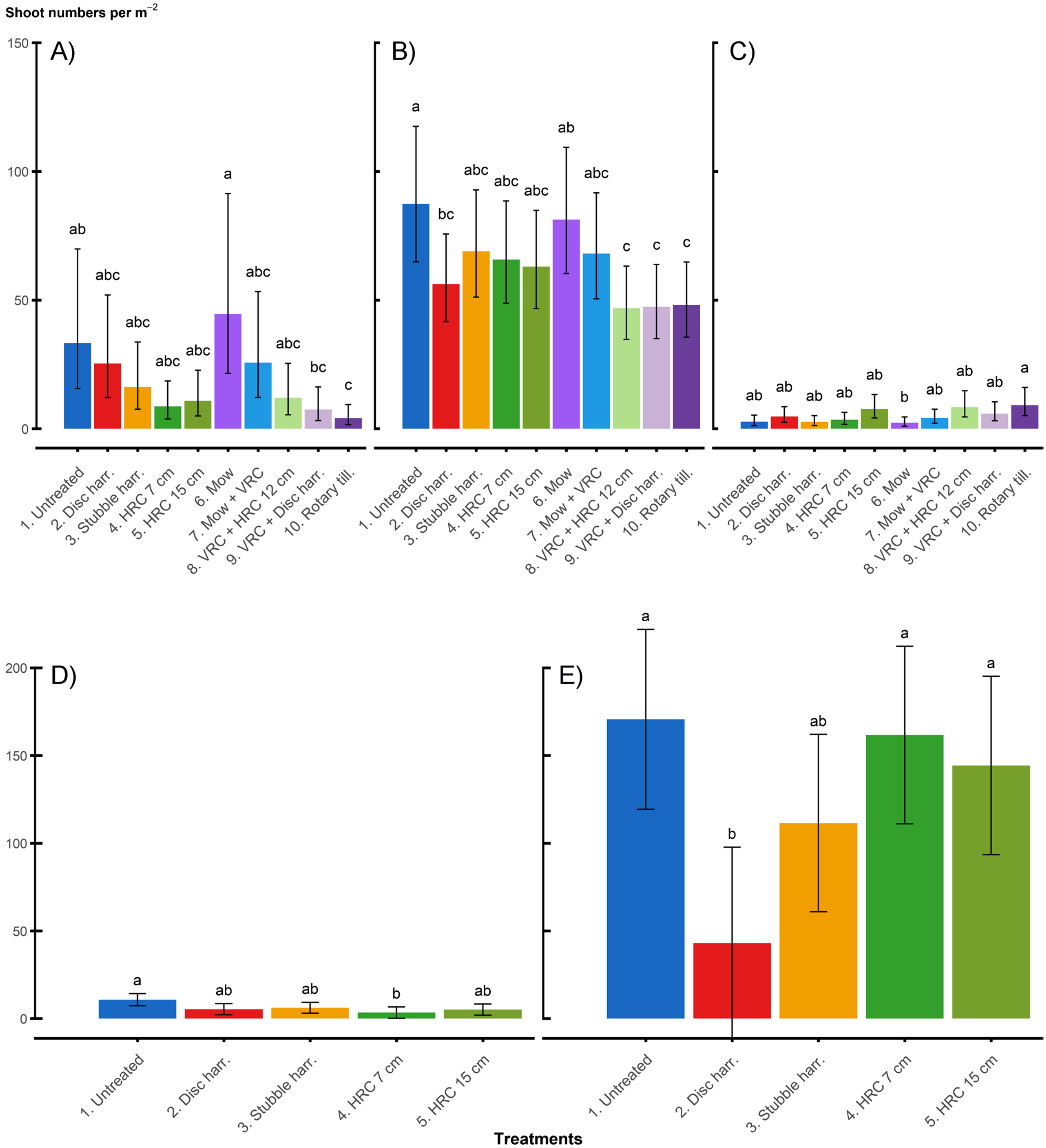

Fig. 4 Results from Experiment 1 in Norway on the effect of different tillage treatments on the shoot numbers of **A**) *E. repens*, **B**) *S. arvensis* and **C**) *S. palustris*, averaged over the sampling years 2017-2019; and Experiment 2 in Sweden on the effect of different treatments on the shoot numbers of **D**) *Cirsium arvense* and **E**) *E. repens*, average over the sampling years 2018-2019. All treatments were plowed in spring each year in Experiment 1, and in autumn in Experiment 2. VRC = vertical root/rhizome cutter, HRC = Horizontal root/rhizome cutter. Letters show the result of Tukey test at α =0.05.

Table 7 ANOVA-table of the effects of treatment and year/time on the shoot numbers of *Elymus repens*, *Sonchus arvensis*, *Stachys palustris*, and *Vicia cracca* in Experiment 1, and on *E. repens* and *C. arvense* in Experiment 2. For Experiment 2 time was used rather than year as shoot numbers were counting twice each year for a total of four times over two years. Different covariates of initial dry weight (DW) or shoot numbers (No) of different perennial weed species were used depending on whether they had a significant effect. LN = natural logarithm.

	Experiment 1 – shoot numbers				Experiment 2 – shoot numbers	
	Elymus repens	*Sonchus arvensis*	*Stachys palustris*	*Vicia cracca*	*Elymus repens*	*Cirsium arvense*
Treatment	**0.004**	**<.0001**	**0.02**	0.4	**0.02**	**0.04**
Year/Time	**<.0001**	**<.0001**	**<.0001**	0.2	**<.0001**	**0.002**
ElymusDW	**0.003**					
SonchusNo	**0.002**		**0.0006**	0.1		
ElymusNo					**0.0002**	
CirsiumNo						**0.003**
Transformation	LN+1	LN+1	LN+1	LN+1		

shoot numbers (Figure 3A and 4A). Rotary cultivation has been shown to greatly suppress and fragment the roots/rhizomes of perennial weeds (e.g., Cussans and Ayres 1977; Skorupinski et al. 2024a) so its impressive that the HRC+VRC could reach similar suppressive results with far less soil disturbance. Similarly, Lötjönen and Salonen (2016) found that the very intensive tillage methods Kvick-Finn and rotary spade harrow reduced decreased *E. repens* shoot biomass by 86–98% and 75%, respectively. Contrasts between treatments with VRC (i.e., mowing+VRC, HRC+VCR and disc harrow+VCR) and treatments without VRC (i.e., mowing, HRC 7 cm, HRC 15 cm and disc harrow) showed that treatments with VRC reduced total perennial weed biomass by 21% (p-value=0.005), *S. arvensis* shoot numbers by 19% (p-value=0.03) and shoot biomass by 22% (p-value=0.03), and *E. repens* shoot biomass by 40% (p-value=0.04) (though not *E. repens* shoot numbers (p-value=0.2)), compared to treatments without VRC.

This is the first time that the VRC has been shown to have a reductive effect on *S. arvensis*, as previous studies have focused on *E. repens*. This can, together with the effect of the HRC, be contrasted with previous work that show a relatively limited effect of root fragmentation on *S. arvensis* growth and reproduction (e.g. Anbari et al. 2011, 2016a, b). That the HRC and HRC+VRC had a relatively high effect on *S. arvensis* is interesting since autumn treatments are generally ineffective against *S. arvensis*. This is because *S. arvensis* shoots die down early in the autumn and its roots enter a state of dormancy (Liew et al. 2013). A reduction of 40% shoot biomass of *E. repens* corresponds well with the 38% shoot biomass reduction achieved with VRC in Ringselle et al. (2018). However, this is surprising as the treatments in Experiment 1 were performed in autumn and only in one direction, while the VRC treatments in Ringselle et al. (2018) were performed in early summer in a crisscross pattern, which should have resulted in a higher efficacy. At least Bergkvist et al. (2017) found that rhizome fragmentation in a crisscross pattern was much more effective against *E. repens* in early summer than in autumn. Brandsæter et al. (2020) also found that the VRC did not significantly reduce *E. repens* shoot biomass when performed in one direction in autumn. That the VRC in the present study was used as part of an integrated strategy may explain why it was effective despite being used in autumn and in only one direction.

3.4 Differences between treatment depths and perennial weed species

There was no support for Hypothesis 3, which stated that shallow root/rhizome tillage treatments would be more effective against perennial weed species with relatively shallow roots/rhizomes, and deeper treatments more effective against those with relatively deep roots. There was little to no difference between the two HRC treatments (7 and 15 cm) in either Experiment 1 and 2 in their effect on perennial weed biomass or shoot numbers, or crop yield. The VRC had a higher effect on *E. repens* than on *S. arvensis*, but this could either be because fewer *S. arvensis* roots were fragmented, or that the fragmentation had a lesser effect on *S. arvensis*. Two factors may have contributed to the minimal difference between the HRC treatments of different depths: 1) the experiments were conducted in a plowed system, and 2) even the deeper treatment was not that deep. In untilled systems *E. repens* rhizomes grow relatively close to the soil surface, while they are distributed down to the plowing depth in plowed systems (Lemieux et al. 1993). Thus, in a plowed system a 15 cm HRC treatment would still affect many *E. repens* and *S. arvensis* roots/rhizomes, but may affect fewer in a

Table 8 The effect of the three different treatments between 2016-2019 in Experiment 3 on surface runoff, soil loss, phosphorous (P), Po4_p (phosphate) and nitrogen (N) leaching. HRC = Horizontal root/rhizome cutter. ± show the confidence intervals at 95%. Letters show the result of Tukey's Honest Significant Difference (HSD) test

	Surface runoff (mm)			Soil loss (kg/ha)			P loss (kg/ha)			Po4_p (kg/ha)			N loss (kg/ha)		
Disc harrow 10 cm depth	213	±186	a	449	−341/+1419	a	0.75	−0.48/+1.37	a	0.07	−0.03/+0.04	a	3.4	−2.7/+14.6	a
Untreated control	193	±186	a	228	−173/+720	ab	0.46	−0.3/+0.85	a	0.06	−0.02/+0.03	a	2.0	−1.7/+8.9	a
HRC 15 cm depth	180	±186	a	183	−139/+578	b	0.36	−0.23/+0.66	a	0.06	−0.02/+0.03	a	1.7	−1.4/+7.4	a
P-value			0.5			0.04			0.06			0.7			0.2

plowless system. A deeper HRC treatment, for example 25 cm depth, might have resulted in a greater contrast in treatment effects. At 25 cm, the HRC would likely fragment far fewer *E. repens* and *S. arvensis* roots/rhizomes even in a plowed system, but still fragment the roots of the much more deeper-rooted *C. arvense*.

3.5 Effects on soil erosion and leaching

There was clear support for Hypothesis 4, which stated that the HRC causes less soil erosion and nutrient leaching than disc harrowing. In Experiment 3, the HRC 15 cm treatment did not result in a higher level of water surface runoff, soil loss or nutrient leaching of P, N or PO4_P compared to the untreated control, and resulted in 60% less soil loss and a tendency (*p*-value=0.06) towards 52% lower P leaching, than the disc harrow (Tables 5 and 8). A strength of the study is that it is a three-year experiment and the results are very clear (i.e., no indication of increase in any measure compared to the untreated control). However, the results are still limited to one site and its soil type/environment, so more studies under more soil types and production systems are needed to generalize to more contexts. Another limitation is that only one HRC treatment was tested in Experiment 3. Tillage treatments are often repeated to control perennial weeds, which can increase the risk of soil and nutrient losses. For example, Aronsson et al. (2015) found that a single duckfoot cultivation in autumn increased N leaching compared to the untreated control (20 vs. 17 kg N ha^{-1}), and that two duckfoot cultivations or two disc harrow cultivations increased the N leaching even further to 26 kg N ha^{-1}. Multiple HRC treatments would most likely have a lower risk than multiple treatments of more intensive tillage such as disc harrowing, but studies are needed to confirm this. Moreover, unlike disc harrowing, the HRC can be performed in a cover crop without killing it, and combining the HRC with a cover crop could further reduce soil and nutrient losses.

3.6 Implications for management

The results show that in plowed systems the HRC can provide a control efficacy of multiple perennial weed species (*E. repens*, *S. arvensis*, *C. arvense*) that is comparable to more intensive tillage methods such as disc harrowing, stubble harrowing and rotary tillage, but with a much lower low risk of water, soil and nutrient losses. Thus, in plowed systems such as organic farming, the HRC is a clear alternative to more intensive tillage for achieving a more environmentally-friendly control of perennial weeds. The results from these experiments indicate that in a plowed system the HRC depth does not need to be adapted to suit different perennial weed species, but the number of perennial weed species that the root cutters have been tested on is still limited. There are many other perennial weed species with different traits that could be relevant, such as *Calystegia sepium* (L.) R.Br. (hedge bindweed) (Rask and Andreasen 2007), *Cyperus aromaticus* (L.) (Navua sedge) (Chadha et al. 2022), *Cyperus esculentus* L. (Yellow nutsedge), (Feys et al. 2023), *Cynodon dactylon* (L.) Pers (Bermudagrass) (Soares et al. 2023) and *Rumex obtusifolius* L. (Broad-leaved dock) (Ringselle et al. 2019). The influence of autumn vs. spring plowing may also need to be studied further, as plowing time may affect the HRC differently than other tillage methods.

With its minimal disturbance of the soil and soil cover, and possibility to combine with cover crops, the root cutters are likely to be very relevant for conservation agriculture, regenerative agriculture and other farming systems that eliminate or strongly reduce the use of tillage, especially plowing. For these systems there are still many questions that need answering, such as how effective the HRC is against perennial weeds when it is not followed by plowing, how effective the HRC is as a part of integrated strategies such as combining it with cover crops, mowing and the VRC, and how the treatments must be adapted to a plowless system. In a recent study, Weigel et al. (2024) showed that the HRC can be effective against *C. arvense* and *E. repens* (and to a lesser extent *S. arvensis*) even without plowing. In fact, when combined with a cover crop the HRC had a similar effect as plowing, which supported the results of Weigel et al. (2023) on *C. arvense*. However, even plowing is generally not sufficient to control perennial weed species on its own, and more knowledge is needed on the long-term effect of using HRC in plowless systems. For instance, with *E. repens* rhizomes growing closer to the surface in untilled systems (Lemieux et al. 1993) it may be necessary to use shallow HRC treatments to control *E. repens* in these systems. A shallower HRC treatment may be far more damaging to a cover crop than a deeper HRC treatment. The fragmentation effect may also be less on roots/rhizomes growing closer to the soil as less energy is needed to reach the soil surface (Håkansson 1967), but this may be compensated for by the use of a cover crop and/or mowing. It is also possible that since less tilled soils can have a higher degree of soil organic carbon, higher microbial and fungal activity and a different microbial community (Krauss et al. 2020) that fragmented roots/rhizomes would break down faster than in plowed soils. Moreover, the shallow rhizomes could also make *E. repens* more susceptible to VRC treatments, increasing the synergy from applying both HRC and VRC.

The results show that the VRC can increase the efficacy of other tillage tools – with the HRC + VRC and disc harrow + VRC treatments being almost indistinguishable from the far more intensive rotary tiller in their effect. That the effect was achieved when only running in one direction, rather than in a crisscross pattern (as in e.g. Ringselle et al. 2018, 2023) increases the potential of the VRC as a control method. Running it twice to achieve a crisscross pattern is very labor intensive and disturbs the soil more. More experiments where the VRC is used, preferably in the spring, as a component of an integrated strategy, would be desirable.

Many questions regarding the potential of the root cutters will not be answered until they are released on the market and more farmers can test their suitability and different uses in their cropping systems, in different soils, climates and against many different weed species. However, there are reasons to believe they will be relatively cheap and flexible tools that will fit many systems. They have a relatively simple design (Figure 1A and C). They can be used in a living cover crop, and they can provide a limited amount of soil disturbance without seemingly increasing the risk of soil and nutrient losses. The time and energy required for using the root cutters can also be expected to be less than more intensive tillage, but further studies are needed to confirm this.

4 Conclusions

The aim of the study was to determine whether the root cutters can control multiple perennial weed species as effectively as more intensive tillage methods in plowed systems in Northern Europe, without increasing the risk of soil and nutrient losses. The results show that the HRC can significantly reduce the biomass and/or shoot numbers of multiple perennial weed species (*E. repens*, *S. arvensis*, *C. arvense*) and increase the crop yield compared to an untreated or mowed control. As hypothesized, the overall effect of the HRC is not worse than more intensive tillage methods such as disc harrow, stubble harrow or rotary tiller. Moreover, as hypothesized, the HRC does not increase soil, water and nutrient losses compared to an untreated control, and results in less soil loss and P leaching than the use of a disc harrow. Contrary to what was hypothesized, in this study, using a HRC treatment depth of 7 or 15 cm did not differ for *E. repens*, *S. arvensis* or *C. arvense* control. However, as hypothesized, treatments that integrated the VRC reduced *E. repens* and *S. arvensis* shoot biomass and shoot numbers more than treatments without VRC but the effect was greater for *E. repens* than for *S. arvensis*.

These findings show for the first time that the HRC can provide a much-needed soil-friendly alternative to more intensive tillage to control perennial weeds in plowed systems, for example in organic agriculture. The results also show the VRC's potential to increase the efficacy of integrated strategies against multiple perennial weed species, and that it can seemingly be effective even if run only in one direction rather than in a crisscross pattern. The root cutters show great potential to be used for perennial weed control in plowless systems to reduce these systems' reliance on herbicides. More studies are needed in both plowed and in plowless systems to show the effect of using the root cutters against more perennial weed species and the cumulative effect over time.

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Authors' contributions Lars Olav Brandsæter (LOB), Trond Børresen (TB), Kjell Mangerud (KJ), Anneli Lundkvist (AL) and Theo Verwijst (TW) acquired the major funding and contributed to the study conception and design. Björn Ringselle (BR) acquired the minor funding. LOB, TB and KJ had the main responsibility for Experiment 1 and 3 and AL and TW the main responsibility for Experiment 2. Torfinn Torp (TT) conducted all statistical analyses. Øystein Skagestad (ØS) collated the management information and wrote a first draft of the introduction and M&M, while BR completed the manuscript and produced all figures. All authors except KJ (deceased) commented on the final draft. BR acted as corresponding author.

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Data Availability Data will be provided upon request.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent to publication Not applicable.

Conflicts of interest The authors declare that there are no conflicts of interest, however for the sake of transparency, please note that Björn Ringselle was an associate editor at the journal of Agronomy for Sustainable Development between 2020-2024.

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