

Root cutters: Novel tillage methods to control creeping perennial weeds with a low risk of soil erosion and nutrient leaching

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Abstract

Perennial weeds are a major obstacle for reducing pesticides and tillage. Three multi-year experiments were conducted in Norway and Sweden to determine if a) the horizontal and vertical root/rhizome cutters (HRC and VRC, respectively) can provide effective non-chemical control of multiple perennial weed species comparable to more intensive tillage methods (Experiments 1–2), b) without increasing the risk of soil erosion and nutrient leaching (Experiment 3), and c) if integrating the VRC with the HRC, mowing or disc harrow can increase the efficacy against perennial weeds (Experiment 1). All treatments were spring plowed in Experiment 1 and 3, and autumn plowed in Experiment 2. In Experiment 1, the rotary tiller was the most suppressive against *Sonchus arvensis* and *Elymus repens* but increased *Stachys palustris* shoot numbers. HRC treatments were not significantly worse than the rotary tiller and increased crop yield by 28%, reduced total perennial shoot biomass by 46–51% and reduced *S. arvensis* and *E. repens* shoot biomass by 52% and 80%, respectively, compared to an untreated control. In Experiment 2, HRC treatments reduced *Cirsium arvense* shoot numbers by 71% compared to the untreated control but failed to control *E. repens*. HRC treatment depth (7 vs. 15 cm) did not significantly affect control efficacy. Experiment 3 showed that HRC 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 VRC reduced the shoot biomass of *E. repens* by 40% and *S. arvensis* by 22%, compared to without VRC. Novelty, the results show that in plowed systems, HRC provides control of multiple perennial weed species that is comparable to more intensive tillage methods, but with little risk of soil and nutrient losses; and integrating VRC into control strategies improves perennial weed control efficacy.

1. Introduction

To create a more sustainable future for humanity, it is imperative to reduce the ecological footprint of our production systems. The reduction or elimination of pesticide use and/or tillage is a common requirement or goal of most agricultural sustainability concepts [e.g., no pesticides allowed in organic farming (Migliorini and Wezel 2017), reduced-till to no-till in conservation agriculture (Nichols et al. 2015), reduced or eliminated tillage and pesticide use in regenerative agriculture (Newton et al. 2020), priority of preventive measures over direct weed control in integrated weed management (IWM) (Riemens et al. 2022)] and programs aimed at increasing agricultural sustainability [e.g., the European Farm to Fork strategy, which aims to reduce pesticide use and nutrient losses in the EU by 50% by 2030 (Wesseler 2022)]. For pesticides this is due to concerns over environmental persistence, groundwater pollution, effects on non-target organisms and toxicity to humans (Van Bruggen et al. 2018) – and as a result many pesticides have been banned or had their use restricted within the EU. Tillage, on the other hand, can both be detrimental to the treated soil by e.g. removing the protective soil cover, destroying soil aggregates and damaging soil-living organisms, but also to the surrounding environment by increasing the risk of soil erosion and nutrient leaching (Klik and Rosner 2020).

Weeds are the major obstacle for reducing pesticides and tillage. On average, the potential of weeds to cause yield losses are more than twice that of other pests such as insects, fungi and pathogens (Oerke 2006). As a consequence, herbicides make up a large proportion of the pesticides sold, especially in cereal and grassland dominated regions such as northern Europe (Antier et al. 2020). Tillage-tolerant creeping perennial weeds, such as *Elymus repens* (L.) Gould (couch grass), *Cirsium arvense* (L.) Scop. (creeping thistle) and *Sonchus arvensis* L. (perennial sow-thistle), are especially problematic to control without herbicides or tillage due to the persistence of their underground storage organs (e.g. thickened roots capable of producing shoots, taproots, tubers, rhizomes) (Håkansson 2003; DiTommaso and Prostak 2021).

In modern industrial agriculture, herbicides are the main control method for perennial weeds, especially glyphosate and other systemic herbicides that are transported down to their underground storage organs, thus killing the whole plant. However, glyphosate is currently facing increasing scrutiny within the EU, and while it was renewed again in 2023, a potential ban is continuously being discussed, which would severely limit the options of conventional farmers (Fogliatto et al. 2020), in particular their ability to control perennial weeds such as *E. repens*, for which alternative herbicides are expensive and/or not allowed in sufficiently high doses for control (Ringselle et al. 2020).

The main alternatives to herbicides to control perennial weeds are using a combination of preventive measures (e.g. the inclusion of regularly mown competitive leys or cover crops, which can be effective against some perennial weed species (Thomsen et al. 2015)) and/or using intensive tillage (e.g., multiple harrowing operations to fragment the roots/rhizomes followed by moldboard plowing) (Ringselle et al. 2020; Soares et al. 2023). An increased use of preventive measures would be beneficial to agricultural sustainability and create more diverse cropping systems which do not promote a few highly competitive weed species like monocultures do (Adeux et al. 2019). However, many effective preventive measures (e.g. leys) are underutilized due to low profitability or other agronomic concerns; and some perennial weed species such as *E. repens* are difficult to control through preventive measures alone. Thus, because of problems with perennial weeds, efforts to reduce herbicide use usually ends up increasing tillage use and vice versa.

While some forms of tillage can have beneficial effects (e.g. reducing some plant diseases (Bankina et al. 2018) and preparing the soil for the next crop), the intensive tillage used to control perennial weeds is energy and time-demanding, and can result in extended periods of bare soil, which increases the risk of soil erosion and nutrient leaching (Aronsson et al. 2015; Klik and Rosner 2020). Intensive tillage is also difficult to combine with cover crops that could otherwise reduce nutrient leaching (Melander et al. 2016); and intensive tillage in spring can delay sowing, which often reduces the yield of spring-sown crops (Brandsæter et al. 2017). Perennial weed species also vary in the traits that affect their susceptibility to different control methods (e.g., underground storage organs occur at different soil depths and with varying degrees of dormancy (Liew et al. 2013)), which complicates control efforts as methods and timing often have to be adjusted to suit each species. There are some non-chemical alternatives to tillage that can destroy roots/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.

The Kverneland Group (together with researchers participating in a series of research projects, starting with the “Optimising Subsidiary Crop Applications in Rotations” (OSCAR) project) have developed two root/rhizome cutter (RC) prototypes that could potentially strike the golden balance between being able to fragment the roots/rhizomes of perennial weeds, but with minimal soil disturbance, and thus theoretically have a low risk of soil and nutrient losses. The first prototype, the vertical RC (VRC; see Fig. 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 which roots/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 RC (HRC), cuts horizontally using wide shears to a maximum depth of 30 cm (see Fig. 1C-D), but the depth can be adjusted as desired, making it potentially effective against both perennial weed species with shallow and deep roots/rhizomes, such as *C. arvensis* which 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 twice can reduce it by 63% (Ringselle et al. 2018). This supported previous results that have shown a large reductive effect of fragmenting the underground storage organs of perennial weed species (e.g., Bergkvist et al. 2017). 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. arvensis* shoot numbers, patch expansion and root carbohydrate content, though in these studies it was not as effective as moldboard plowing (Weigel and Gerowitt 2022; Weigel et al. 2023).

So far, no studies have been published that demonstrate the efficacy of the RCs in controlling multiple perennial weed species with different root/rhizome traits, nor how the RCs 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 comparing the RCs' effect on multiple perennial weed species over multiple years compared to other tillage treatments (Experiment 1 & 2), the effect of combining the VRC with other tillage treatments (Experiment 1), and the effect of the HRC on soil erosion and nutrient leaching (Experiment 3). The tested hypotheses were that: 1) the RCs will result in significantly less perennial weed biomass and shoot numbers, and higher crop yield, than an untreated control and mowing, and will not have a significantly worse effect than more intensive tillage methods (i.e. disc harrows, stubble harrows and rotary tillers), 2) integrating VRC with other control methods (e.g. HRC, disc harrow, mowing) will increase the control efficacy against perennial weeds, 3) perennial weed species with relatively shallow roots/rhizomes such as *E. repens*, *S. arvensis*, *Vicia cracca* L. (tufted vetch) and *Stachys palustris* L. (marsh woundwort) (typical growth depth of the regenerative plant organs of these species is up to 10–30 cm, with species ordered from most to least shallow), will be more affected by a shallow treatment (i.e. the VRC, or the HRC used at 7 cm depth), while perennial weed species with deeper roots/rhizomes such as *C. arvensis* will be more greatly reduced by a deeper treatment (i.e. the HRC used at 15 cm depth), and 4) using the HRC in the cereal stubble will not increase the water, soil and nutrient losses compared to an untreated control, but will result in significantly lower losses than using a disc harrow.

2. Materials and Methods

2.1. Experiment 1 and 2

2.1.1 Study sites, experimental design and treatments

Experiment 1 was performed in Ås, Norway (59°66'N 10°76'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. arvensis*, *S. palustris* and *V. cracca* that dominated the weed flora, and there were no prominent annual weeds. All plots were fertilized with dried chicken manure [“Marhøne 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.

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. arvensis* 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.

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, 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) VRC 12 cm depth + HRC 12 cm depth, 9) VRC 12 cm depth + Disc harrow 12 cm depth, and 10) Rotary tiller 12 cm depth. Implement specifications for the treatments are provided in Table 4. In both the VRC + HRC and VRC + Disc harrow 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) there 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 m² (thus, 2 m² 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 m² randomly placed quadrants (4 m² 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 m²). For shoot biomass four subplots with an area of 0.25 m² were randomly selected in each plot (thus, 1 m² 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 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

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 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. 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. Precipitation was recorded manually 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 $\ln(\cdot)$ 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.).

3. Results and discussion

3.1 Initial perennial weed abundance and yearly variation

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. arvensis* and 7.1 *C. album* plants m^{-2} in Experiment 2. *Stachys palustris*, *V. cracca* and *C. arvensis* in Experiment 1 were not counted pre-treatment.

There was a great deal of yearly variation within the data, but almost no interactions between year and treatment (Table 5–8). One major factor for the yearly variation was the 2018 summer drought, which resulted in a much lower 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. arvensis*. 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.

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

In Experiment 1, the rotary tiller resulted in the highest cereal yield, 40% higher than the untreated control and approximately 27% higher than the mowed or mowing + VRC treatments (Fig. 2A; Table 5). The disc harrow (+30%), HRC at 7 cm depth (+28%), VRC + HRC (+33%) and VRC + disc harrow (+36%) treatments also resulted in significantly higher cereal yields than the untreated control (Fig. 2A). In Experiment 2 there was no significant difference in crop yield between treatments (Fig. 2B; Table 5).

In Experiment 1, the rotary tiller had the greatest effect on the total perennial weed biomass (-67%), compared to the untreated control, but the effect was not significantly greater than the VRC + HRC (-66%), VRC + disc harrow (-66%), HRC 15 cm (-51%), disc harrow (-51%) or HRC 7 cm (46%) treatments (Fig. 3; Table 6). Similar to crop yield, the stubble harrow, mowing and mowing + VRC treatments did not significantly reduce total perennial weed biomass. In Experiment 2 there was no significant difference between treatments for total perennial weed biomass, only for shoot numbers (Table 7).

On a species level, in Experiment 1, the rotary tiller was the most suppressive of *E. repens* and *S. arvensis*, reducing *E. repens* biomass by 94% and shoot numbers by 88%, and *S. arvensis* biomass by 65% and shoot numbers by 45%, compared to the untreated control (Fig. 3–4; Table 6–8); though the VRC + disc harrow and VRC + HRC treatments had an almost identical effect on *E. repens* and *S. arvensis* except that they did not quite significantly reduce the number of *E. repens* shoots compared to the untreated control (Fig. 3–4). On its own, the disc harrow did not quite significantly reduce *E. repens* biomass or shoots numbers, but reduced *S. arvensis* biomass by 56% and shoot numbers by 36%, compared to the untreated control. The HRC treatments (7 cm and 15 cm depth) hovered around significantly reducing both *E. repens* and *S. arvensis*, with the 7 cm treatment significantly reducing *S. arvensis* biomass by 52% and the 15 cm treatment significantly reducing *E. repens* biomass by 80%, and while neither significantly reduced their shoot numbers on their own, the contrast between the two HRC treatments and the untreated control showed a significant reduction in both *E. repens* (-71%; $P = 0.01$) and *S. arvensis* (-26%; $P = 0.004$) shoot numbers. In Experiment 2, the disc harrow reduced the number of *E. repens* shoots by 75% compared to the untreated control, while the HRC 7 cm reduced the number of *C. arvensis* shoots by 71% (Fig. 4B); the same pattern could be seen for the perennial weed biomass, but without significant differences (Fig. 3B). In Experiment 1, *S. 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; Fig. 4A; 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) which, in combination with the decrease in its competitors, could explain its increase in the tilled treatments that reduced *E. repens* and *S. arvensis*. There was no significant treatment effect on *V. cracca* in Experiment 1 (Table 6–8), which may be explained by relatively patchy occurrence of *V. cracca* in the field compared to *E. repens* and *S. arvensis*.

Hypothesis, which stated the RCs would result in significantly less perennial weed biomass and shoot numbers, and higher crop yield, than the untreated control and mowing, but would not have a significantly worse effect than more intensive tillage methods (i.e. disc harrows, stubble harrows and rotary tillers), was mostly supported for the HRC, but only partly for the VRC. Overall, the HRC treatments reduced the weed biomass and/or shoot numbers of *E. repens*, *S. arvensis* and *C. arvensis* compared to mowing and the untreated control and was almost never significantly worse than the more intensive tillage treatments, with the clearest exception being the failure to control *E. repens* in Experiment 2 despite an 80% reduction of *E. repens* shoot biomass in Experiment 1. One reason for this failure could be because autumn plowing was used in Experiment 2 (compared to spring plowing in Experiment 1), which means that the plowing was conducted relatively soon after the HRC was used – potentially reducing the impact of the HRC treatment. 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. arvensis*, most likely because the effect was too similar (Brandsæter et al. Unpublished). 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. arvensis* and *S. arvensis* (Brandsæter et al. 2017); but 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. arvensis*, supporting previous studies that fragmenting the roots/rhizomes of perennial weeds has a negative effect on their growth and propagation (e.g. Thomsen et al. 2013; Ringselle et al. 2018). 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 compensated by the 2–3 year duration of the experiments.

No treatment with VRC (Mow + VRC, HRC + VCR, disc harrow + VCR) in Experiment 1 reduced *E. repens* or *S. arvensis* biomass or numbers significantly more than the corresponding treatment without VRC (mowing, HRC 7 cm, HRC 15 cm or disc harrow). However, contrasts between the two treatment groups showed that treatments with VRC reduced total perennial weed biomass by 21% ($P = 0.005$), *S. arvensis* shoot numbers by 19% ($P = 0.03$) and

shoot biomass by 22% ($P = 0.03$), and *E. repens* shoot biomass by 40% ($P = 0.04$) (though not *E. repens* shoot numbers ($P = 0.2$)), compared to treatments without VRC. These results support Hypothesis 2, which stated that integrating the VRC with other control methods would increase the efficacy against perennial weeds. 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*; and 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). 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), even though the treatments in Experiment 1 were performed in autumn and only in one direction rather than, as in Ringselle et al. (2018), being performed in early summer in a crisscross pattern. Bergkvist et al. (2017) found that, at least for *E. repens*, rhizome fragmentation in a crisscross pattern is much more effective in early summer than in autumn. Brandsæter et al. (2020) found that the VRC did not significantly reduce *E. repens* shoot biomass when performed in one direction in autumn.

The results provided little to no support to Hypothesis 3, which stated that shallow root/rhizome fragmentation would be more effective against perennial weed species with relatively shallow roots/rhizomes, and deeper fragmentations 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. However, 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 in a plowless system it might fragment fewer roots/rhizomes, especially for *E. repens*. A deeper HRC treatment, for example 25 cm depth, might have resulted in a greater contrast in treatment effects as, even in a plowed system, it would likely affect fewer *E. repens* and *S. arvensis* roots/rhizomes but still be likely to be effective against the more deeper-rooted *C. arvense*.

3.3 Effects on soil erosion and leaching

The results showed clear support for Hypothesis 4, which stated that using the HRC in the cereal stubble will not increase the water, soil and nutrient losses compared to an untreated control, but will result in significant lower losses than using a disc harrow. 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 ($p = 0.06$) towards 52% lower P leaching, than the disc harrow (Tables 5 & 8). The results are limited to one site and its soil type/environment, but the fact that it is a three-year experiment, and the clearness of the results (i.e. no indication of increase in any measure compared to the untreated control), provides a good indication that the results may be generally applicable, but more studies under more soil types and production systems are needed. Another limitation is that only one HRC treatment was tested in Experiment 3, using it once in autumn, while in Experiment 1–2, the stubble treatments were sometimes repeated – which is often the case and could potentially increase the risk of soil and nutrient losses. Yet even multiple HRC treatments would most likely have a lower risk than multiple treatments of more intensive tillage such as disc harrowing. 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. 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.

3.4 Implications for management

The results show that in a plowed system 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 risk of water, soil and nutrient losses. Thus, the HRC is a clear alternative to more intensive tillage for achieving a more environmentally friendly control of perennial weeds in plowed systems, for example in organic farming. 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 further studies on HRC depth are needed. 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 HRC is 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. 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, but this could 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 (Kolberg et al. 2018); and it is possible that since less tilled soils can have a greater soil health with 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. Some of these questions have been studied in the AC/DC-weeds-project (*Applying and Combining Disturbance and Competition for an agro-ecological management of creeping perennial weeds*) that ran 2019–2022 and/or will be studied in the SUSWECO-project (*Sustainable weed control in cereals by combining subsidiary crops and minimal soil disturbances*) that will run 2023–2027. The results that have been published from AC/DC-weeds so far show that, without plowing, up to six

HRC treatments may be needed to achieve sufficient control of *C. arvense* (Weigel and Gerowitt 2022), yet only two HRC treatments combined with a cover crop was sufficient to reduce *C. arvense* expansion to the same degree as plowing (Weigel et al. 2023).

The results show that even though the VRC did not provide very high suppression of perennial weeds (which is congruent with previous results), when combined with other tillage methods (e.g. HRC, disc harrow), it increased the efficacy – with the VRC + HRC and VRC + disc harrow 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 as a crisscross patterns (as in e.g. Ringselle et al. 2018, 2023) increases the potential of the VRC as a control method as 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. For example, a spring VRC application in a cereal crop followed by post-harvest HRC applications in a cover crop could potentially be a very potent strategy to control multiple perennial weed species with a very low risk of soil erosion and nutrient leaching.

The experiments have shown that the RCs can be effective against multiple perennial weed species with different traits. It can be hypothesized that they would be effective against other perennial weed species that are negatively affected by rhizome/root fragmentation, such as *Calystegia sepium* (L.) R.Br. (hedge bindweed) (Rask and Andreasen 2007), and *Cyperus aromaticus* (L.) (Navua sedge) (Chadha et al. 2022), but it would have to be tested to be confirmed. It would be especially interesting to test the RCs against perennial weed species with other types of underground storage organs such as *Cyperus esculentus* L. (Yellow nutsedge), which has rhizomes and tubers (Feys et al. 2023), *Cynodon dactylon* (L.) Pers (Bermudagrass), which has rhizomes and stolons (Soares et al. 2023), and against *Rumex obtusifolius* L. (Broad-leaved dock) which has a large taproot (Ringselle et al. 2019).

4. Conclusions

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. Overall, the effect of the HRC is not worse than more intensive tillage methods such as disc harrow, stubble harrow or rotary tiller. Moreover, 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. 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. Overall, treatments that integrated the VRC reduced *E. repens* and *S. arvensis* shoot biomass and shoot numbers more than treatments without VRC but was more effective against *E. repens* than *S. arvensis*.

Novelly, the results show 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. In addition to organic farming, the RCs show great potential to be used for perennial weed control in plowless systems to reduce these systems' reliance on herbicides, but more studies are needed in such systems.

Declarations

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Conflicts of interest

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

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent to publication

Not applicable.

Availability of data and material

Data will be provided upon request.

Code availability

Not applicable.

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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Tables

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	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 / 2 nd 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	

*Spring barley (2016: cv. "Thule" 210 kg/ha, 2017: cv. "Brage" 200 kg/ha), Oats (2018: cv. "Niklas" 220 kg/ha, 2019: cv. "Niklas" 230 - 240 kg/ha)

**Spring barley 400 kernels/plot, all years

***Spring oat 210 kg/ha, all years

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.

	Mean temperature (°C)					Radiation (Σ MJ m ⁻²)					Precipitation (Σ 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

*means for the period 1991–2020

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).

	Mean temperature (°C)				Radiation (Σ MJ m ⁻²)				Precipitation (Σ 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

*means for the period 1991–2020

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	-	

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), Po4_p (phosphate) and nitrogen (N) leaching in Experiment 3. Initial number (No) of *Elymus repens* shoots was used as a covariate for crop yield as 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

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.

	Shoot biomass							
	Experiment 1					Experiment 2		
	<i>Elymus repens</i>	<i>Sonchus arvensis</i>	<i>Stachys palustris</i>	<i>Vicia cracca</i>	Total per. weed biomass	<i>Elymus repens</i>	<i>Cirsium arvense</i>	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			

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.

	Weed numbers						
	Experiment 1				Experiment 2		
	<i>Elymus repens</i>	<i>Sonchus arvensis</i>	<i>Stachys palustris</i>	<i>Vicia cracca</i>	<i>Elymus repens</i>	<i>Cirsium arvense</i>	
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			

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. $\pm$ show the confidence intervals at 95%.

	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

Figures

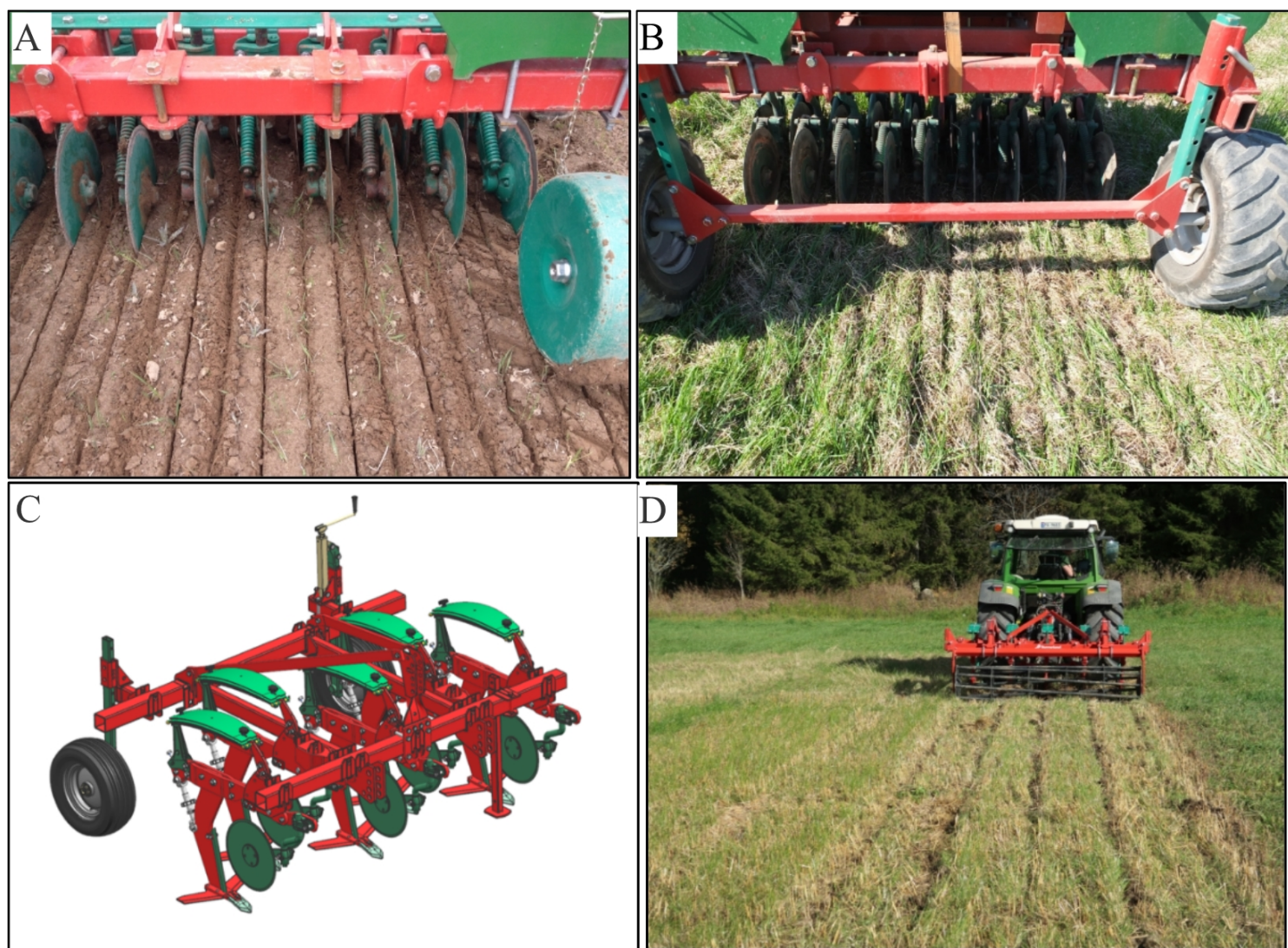


Figure 1

The vertical root/rhizome cutter (VRC) used in soil (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.

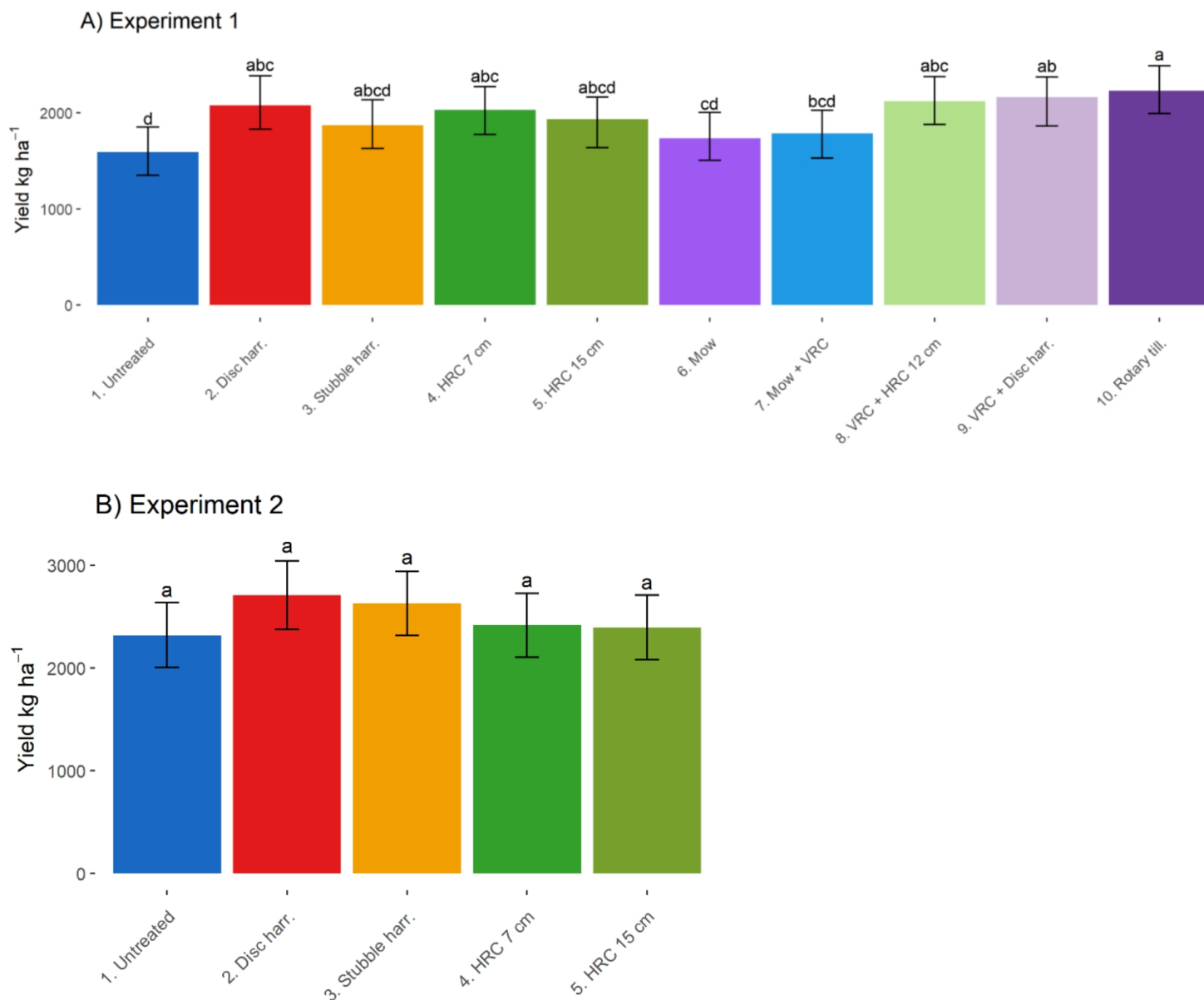


Figure 2

weed biomass. Results from A) Experiment 1 in Norway on the effect of different treatments on the aboveground shoot dry weight (DW) biomass of *E. repens*, *S. arvensis* and 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 B) Experiment 2 in Sweden on the effect of different treatments on the shoot DW biomass of *C. arvense* and *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 $\alpha = 0.05$.

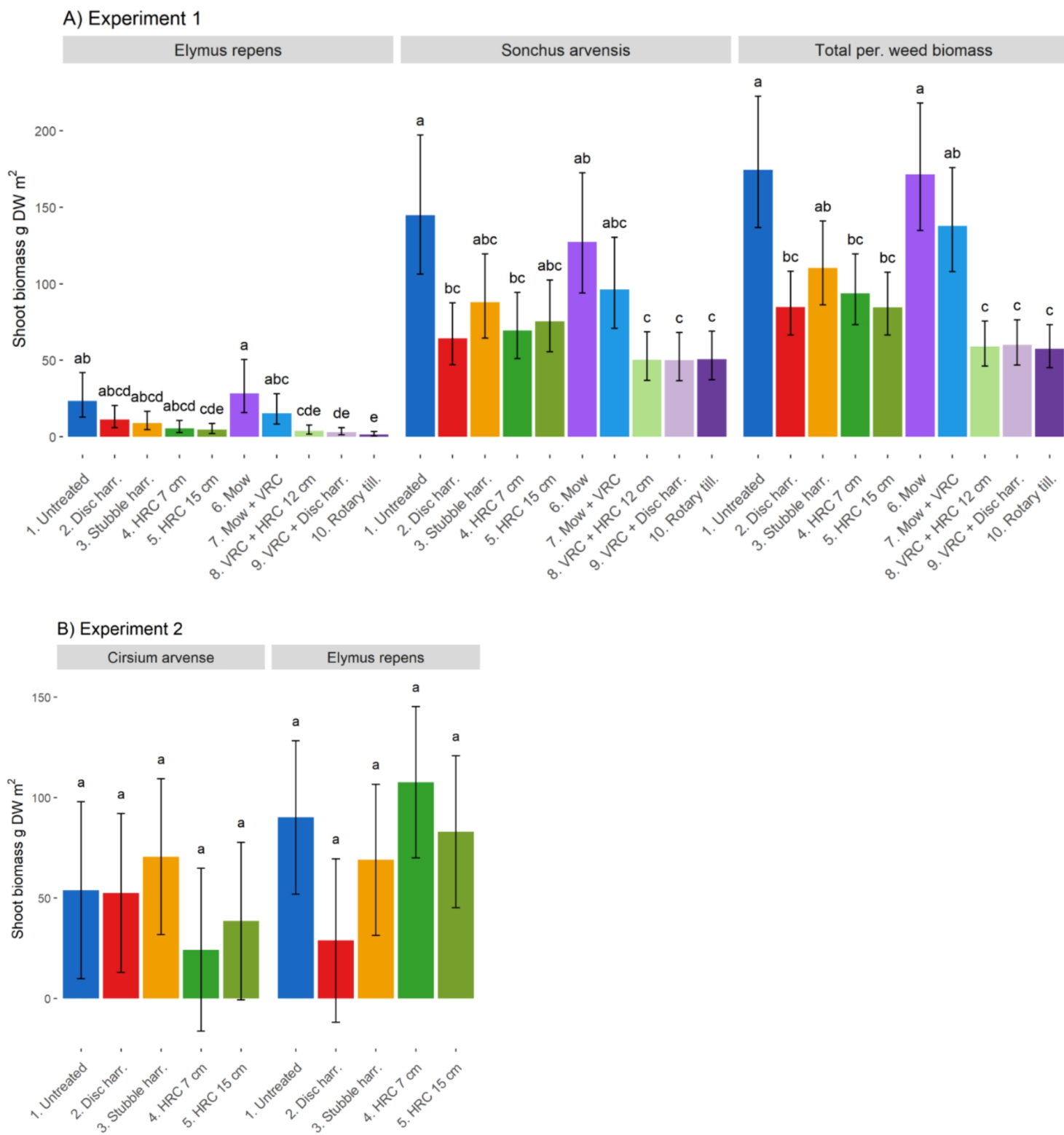


Figure 3

weed numbers. Results from A) Experiment 1 in Norway on the effect of different tillage treatments on the shoot numbers of *E. repens*, *S. arvensis* and *S. palustris*, averaged over the sampling years 2017-2019; and B) Experiment 2 in Sweden on the effect of different treatments on the shoot numbers of *Cirsium arvense* and *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 $\alpha = 0.05$.

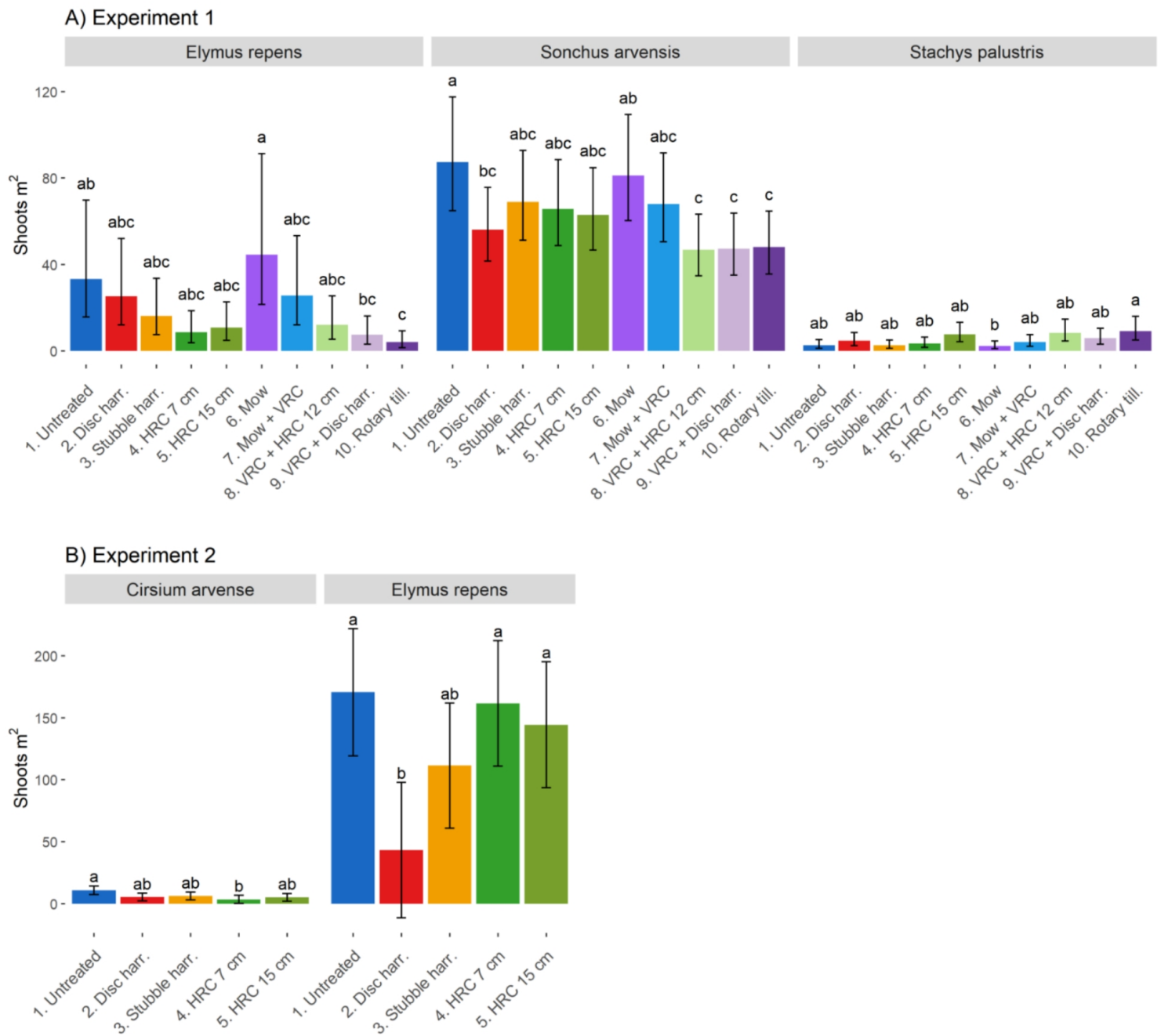


Figure 4

Crop yield. 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 $\alpha = 0.05$.