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Effects of renewal time, taproot cutting, ploughing practice, false seedbed and companion crop on docks (*Rumex* spp.) when renewing grassland

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Abstract

Docks (*Rumex* spp.) are a considerable problem in grassland production worldwide. We investigated how different cultural management techniques affected dock populations during grassland renewal: (I) renewal time, (II) companion crop, (III) false seedbed, (IV) taproot cutting (V), plough skimmer and (VI) ploughing depth. Three factorial split-split plot experiments were carried out in Norway in 2007–2008 (three locations), 2008–2009 (one location) and 2009 (one location). After grassland renewal, more dock plants emerged from seeds than from roots. Summer renewal resulted in more dock seed and root plants than spring renewal. Adding a spring barley companion crop to the grassland crop often reduced dock density and biomass. A false seedbed resulted in 71% fewer dock seed plants following summer renewal, but tended to increase the number of dock plants after spring renewal. In some instances, taproot cutting resulted in less dock biomass, but the effect was weak and inconsistent, and if ploughing was shallow (16 cm) or omitted, it instead increased dock root plant emergence. Fewer root plants emerged after deep ploughing (24 cm) compared to shallow ploughing, and a plough skimmer tended to reduce the number further. We conclude that a competitive companion crop can assist in controlling both dock seed and root plants, but it is more important that the renewal time is favourable to the main crop. Taproot cutting in conjunction with ploughing is not an effective way to reduce dock root plants, but ploughing is more effective if it is deep and a skimmer is used.

Key Words: Cover crop; plow skimmer; plowing depth; *Rumex longifolius*; *Rumex obtusifolius*; *Rumex crispus*

[1]CC = Companion crop
FS = False seedbed
VA07 = Valdres 2007
TI07 = Tingvoll 2007
TR07 = Tromsø 2007
TI08 = Tingvoll 2008
MY09 = Mysen 2009

1. Introduction

Broad-leaved dock (*Rumex obtusifolius* L.) and curled dock (*Rumex crispus* L.) are among the most troublesome perennial weeds in grassland production throughout the world (Zaller, 2004); joined in Northern Europe by the far less studied northern dock (*Rumex longifolius* DC.) (Fykse, 1986). Docks reduce the yield quality and quantity of grasslands (Marten et al., 1987; Hejduk and Doležal, 2004). A study by Oswald and Haggar (1983) found that ten *R. obtusifolius* plants m^{-2} covered 30% of the ground and reduced perennial ryegrass yield by 30%. The most common control methods for docks in conventional farming are selective herbicides or grassland renewal by non-selective herbicides (primarily glyphosate) or ploughing. In Central Europe, Galler (1989) estimated that more than 80% of all herbicides used in conventional grassland were used against docks. In organic farming, the problem is so severe that many farmers are forced to manually weed docks, making it a bottleneck to the expansion of organically managed grasslands (Andersson, 2007; Turner et al., 2007). New management techniques that efficiently manage dock populations are needed to reduce herbicide use in conventional farming and facilitate the expansion of organic grassland.

Docks are perennial dicots that produce taproots and a large number of seeds per plant (Cavers and Harper, 1964). Dock seeds can remain viable even after several decades in the soil (Kivilaan and Bandurski, 1981) and digestion by animals only kills a proportion of the seeds (Harrington et al., 2011; Rahimi et al., 2016). While initially vulnerable to competition, their large taproots give docks an advantage over grassland crops once the docks are established, and allows them to survive many forms of tillage; *R. obtusifolius* produces larger roots than *R. longifolius*, which produces larger roots than *R. crispus* (Fykse, 1986). *Rumex obtusifolius* also benefits more from nutrient applications (particularly N) than *R. crispus* (Strnad et al., 2012). Due to their taproots, docks can survive the regular defoliation inherent in grassland production better than most other weeds (Zaller, 2004). *Rumex obtusifolius* is particularly resistant to defoliation, more so than *R. crispus* (Strnad et al., 2012). In fact, a too high cutting frequency can harm the grassland crop more than the docks; Hann et al. (2012) found that reducing the cutting frequency can sometimes lead to a lower dock abundance. The combination of durable taproots and large seed banks means that dock populations tend to increase with increasing grassland age (Håkansson, 2003), and are therefore particularly problematic in permanent grassland and older leys.

A major aspect of grassland management is grassland renewal; representing both a great opportunity and great risk to dock management (Harrington et al., 2013). Grassland renewal is generally performed by re-sowing after ploughing. Ideally, ploughing will either directly kill the dock plants or place them at a greater depth, where they have to use significant resources to re-shoot. However, similar to other perennial weeds (Håkansson, 2003), tillage, such as ploughing, can also stimulate dock emergence (Zaller, 2004). Not all taproot fragments will be placed at ploughing depth, and large taproot fragments can produce shoots that reach the surface from commonly used ploughing depths (Pino et al., 1995; Pye et al., 2011). While ploughing can bury seeds deeper in the soil where they will not germinate, it can also bring up seeds to the surface. Moreover, only a brief exposure to light is needed for dock seeds to germinate, therefore soil disturbance can result in a large increase in germinating dock seeds (Pye and Andersson, 2009; Harrington et al., 2013). Thus, the challenge lies in finding techniques that are potent enough to destroy the established dock plants, without using too many resources, and without allowing re-establishment from root or seed. A combination of techniques is likely needed to manage both dock root and seed plants.

A number of ways have been suggested to reduce dock emergence following grassland renewal. Renewal time is likely to affect the seed germination rate, but may also affect the re-shooting capacity of disturbed taproots. Undisturbed dock seeds tend to germinate more during times of great temperature fluctuation, particularly in spring (Van Assche and Vanlerberghe, 1989). Hence, performing the grassland renewal in summer rather than spring may reduce the number of germinating seed plants, and would allow for a harvest before ploughing in the renewal year. Following ploughing with a false seedbed, i.e. harrowing to stimulate germination and then to kill the resulting plants before crop sowing, is another way to reduce the number of seed plants (Harrington et al., 2013). Sowing the grassland crop together with a competitive companion crop could also reduce the number of dock seed plants, as dock seedlings are not considered particularly competitive during establishment (Cavers and Harper, 1964; Zaller, 2004).

Treatments prior to ploughing, and optimization of ploughing practices, could potentially increase the efficacy of ploughing on dock root plants. Fragmenting the underground storage and proliferation organs is a common method for weakening perennial weeds before ploughing (e.g. *Elymus repens*, Ringselle et al., 2016; Ringselle et al., 2018). Several studies suggest that in docks, reshooting only occurs from the top part of the taproot (Fykse, 1986; Pino et al., 1995; Bond et al., 2007). Thus, if this part is cut prior to or in conjunction with ploughing, it would reduce the amount of resources root plants have available for reshooting. Such a strategy may be especially effective against *R. longifolius* (Appendix A4). Fykse (1986) found that *R. longifolius* produced significantly more shoots following fragmentation than *R. crispus*, which in turn produced more shoots than *R. obtusifolius*, despite the latter species generally having the heaviest roots. Deep ploughing has been shown to be more effective than shallow ploughing for *R. obtusifolius* (Pino et al., 1995), and may increase the effectiveness of taproot cutting. The ploughing efficacy on docks may also be affected by whether a skimmer is attached or not. A skimmer makes it harder for weeds to emerge following mouldboard ploughing, by slicing off the part of the topsoil that would otherwise be close to the surface following inversion, and instead placing it at the bottom of the furrow. In a four-year experiment, Gummesson and Svensson (1973) found that continuous use of a plough with a skimmer reduced the amount of *E. repens* by 30%, compared to ploughing without a skimmer.

Many studies have tested individual techniques for managing docks, but few have tested a combination of several different techniques. The aim of this study was to investigate combinations of cultural management techniques thought to result in a low number of dock root and seed plants and good crop establishment following grassland renewal. The six hypotheses tested were: following grassland renewal, there will be fewer seed plants when (A) the grassland is renewed in summer, rather than in spring, (B) a competitive companion crop is sown together with the grassland crop, or (C) ploughing is followed by a false seedbed, and there will be fewer emerging root plants when (D) dock taproots are cut in conjunction with ploughing, (E) the plough has a skimmer attached or (F) deep ploughing is used. The hypotheses were tested in three experiments. Experiment 1 tested hypotheses A, B and D, Experiment 2 tested hypotheses A, C and D and Experiment 3 tested hypotheses D, E and F.

2. Materials and methods

2.1 Site Description

Experiments were held at four locations in Norway: (1) Valdres, southern alpine zone; (2) Tingvoll, west coast; (3) Tromsø, north of the Arctic Circle; (4) Mysen, continental south-east (more details in Table 1). All experimental fields were dominated by grassland in the decades preceding trial establishment. At Tingvoll and Mysen, the grassland had been farmed organically for more than 20 years, while the other two locations had been managed conventionally. During the experimental period all sites were managed organically (in line with the national regulations for organic farming; i.e. no herbicides or synthetic fertilizer were used). Prior to the trial period, ploughing to 20–25 cm depth was normally performed in spring when renewing the grassland. Dock populations at the experimental fields were dominated by *R. longifolius*, except at Tingvoll, which had a mixed population of *R. longifolius*, *R. obtusifolius* and *R. crispus*.

2.2 Trial Descriptions

Three split-split plot experimental designs (Gomez and Gomez, 1984) were used to test the six hypotheses, with four replicates at each location. In all three experiments, main plots were 20*8 m, with 10 m between replicates and 3 m between the main plots within the replicates. Split plots were 10*8 m and split-split plots 8*5 m.

2.2.1 Experiment 1

Experiment 1 was conducted from 2007 to 2008 at Valdres (VA07), Tingvoll (TI07) and Tromsø (TR07). It tested renewal time (in spring, or in summer after the first harvest) in the main plots, taproot cutting (yes/no) in the split-plots, and the use of a spring barley (*Hordeum vulgare* L.; 100 kg ha^{-1}, yes/no) companion crop in the split-split plots. To cut the taproots, a rotary tiller (Howard Rotovator with L-shaped knives, see Appendix A1) was used. The rotary tiller was adjusted to a working depth of 6–8 cm for the knives. Since the rotary tiller was operated at 2 km h^{-1}, the calculated distance between cuts was 2.6 cm.

2.2.2 Experiment 2

Experiment 2 was conducted from 2008 to 2009 at the same locations as Experiment 1. However, after establishment, it was determined that there were not enough dock plants at Valdres and Tromsø in 2008. So these experiments were discarded, leaving only Tingvoll (TI08). Similar to Experiment 1, Experiment 2 tested renewal time (spring or summer) in its main plots and taproot cutting (yes/no) in its split plots. In the split-split plots, however, Experiment 2 tested the use of a false seedbed (yes/no) instead of a companion crop. Unlike Experiment 1, taproot cutting was done by replacing the skimmer on the plough with a modified version of the body of a Kverneland Ecomat (Kverneland ASA, Norway) (Appendix A2); a normal skimmer only cuts part of the furrow, while the modified Kverneland Ecomat skimmer was designed to cut along the entire furrow breadth. The false seedbed was achieved by harrowing three times with an S-tine harrow at 5 cm depth, with one week between each harrowing (dates in Table 2).

2.2.3 Experiment 3

Experiment 3 was conducted in 2009 at Mysen (MY09). The main plots in Experiment 3 tested ploughing depth (16 or 24 cm), the split-plots tested taproot cutting (yes/no) and the split-split plots tested the addition of a skimmer on the mouldboard plough (yes/no). Experiment 3 used a third cutting method for cutting the dock taproots: a custom-made knife, mounted behind the skimmer, cut the taproots at 6–7 cm depth across the entire furrow breadth (Appendix A3). At 16 cm ploughing depth, there was too little distance between the knife and the plough's point. This resulted in less even taproot cutting compared to 24 cm ploughing depth, as material got stuck in the gap and reduced the ploughing depth, so that the plough could not turn the furrow and cover the taproots as well as when ploughing at 24 cm.

2.2.4 Grassland establishment

Ploughing during grassland renewal was conducted with a Kverneland mouldboard plough (Kverneland ASA, Norway) equipped with disk coulters and skimmers (dates in Table 2). Experiment 1 and 2 were ploughed to a depth of 23–25 cm, and Experiment 3 according to treatment (16 or 24 cm). After ploughing, plots were harrowed using a S-tine harrow with 10 cm tine distance. In Experiment 1 and 2, cattle slurry (30 t ha^{-1}) was applied in spring, prior to any treatments. The grassland was sown with the grass-clover mixture Strands 'Eco-mix' (35 kg ha^{-1}), which can be regionally adjusted. At Valdres and Tingvoll, the regional mix used was 'Eco-mix for south Norway' [55% *Phleum pratense* L. (timothy) cv. Grindstad, 20% *Festuca pratensis* Huds. (meadow fescue) cv. Sigmund, 10% *Poa pratensis* L. (Kentucky bluegrass) cv. Entopper, 10% *Trifolium pratense* L. (red clover) cv. Nordi and 5% *T. repens* L. (white clover) cv. Nordstar]. At Tromsø, the regional mix used was 'Eco-mix for north Norway' (55% timothy cv. Vega, 20% meadow fescue cv. Kasper, 10% Kentucky bluegrass cv. Entopper, 10% red clover cv. Reipo and 5% white clover cv. Milkanova). Experiment 3 was carried out without fertilization or sowing grassland; the aim was to investigate how the experimental factors affected dock root plant emergence.

2.3 Assessments

In Experiments 1 and 2, assessments were conducted in both the treatment year and the year after treatment, while Experiment 3 only ran from May to June in the treatment year (sampling dates in Table 2). Three types of assessments were conducted: dock density, dock and crop biomass, and vegetation ground coverage.

Dock plants were counted before treatment to account for in-field variation, and three–four times after treatment (Table 2). In the first post-treatment assessment, the plants were divided into root and seed plants. This division was not feasible in the subsequent assessments, as root and seed plants were not sufficiently distinguishable. In Experiment 3, only root plants were counted. Docks were counted in the central part of the split-split plots, by placing 0.25, 0.5 or 1 m^2 quadrats. In general, the quadrats were placed enough times to equal 6 m^2 except for seed plants and root plants at VA07 (2 and 1.5 m^2, respectively), seed plants at TI08 (1 m^2), and root plants at MY09 (5 m^2).

Aboveground plant biomass was harvested in the central part of the split-split plot (approximately 7 m^2) at all sites except VA07. Here, the aboveground plant biomass was manually harvested; the dock biomass in 3.2 m^2 per split-split plot and crop and other weed biomass in 0.8 m^2 quadrats. The dock biomass was separated from the rest of the biomass sample (main crop, companion crop and non-dock weeds), and then both partitions were dried for 72 h at 60 ºC and weighed. At TR07, only fresh weight was recorded for the crop and non-dock weed biomass. At all sites, non-dock weed biomass consisted almost exclusively of annual weeds.

2.4 Statistical Analysis

Dock numbers and biomass were converted to plants m^{-2} and g m^{-2} before statistical analyses. When necessary, data was $\log_e$ (n+1) transformed, and LSMEANS retransformed for use in graphs. The data were analysed using the PROC GLIMMIX procedure in SAS 9.4 (SAS Institute Inc.).

To investigate the main effects of the three factors of the split-split plot experiments and how they interacted with one another, mixed models appropriate for the analysis of split-split plot experiments were modelled. Main effects and their interactions were treated as fixed, and replicate, main plots and split-plot as random effects. Main effects in Experiment 1 were renewal time, taproot cutting and companion crop (Appendix B), in Experiment 2 effects were renewal time, taproot cutting and false seedbed (Appendix C), and in Experiment 3 effects were taproot cutting, ploughing depth and skimmer use (Appendix D). The pre-treatment assessment was included in all models as a covariate to account for in-field variation, but is also displayed in Figure 1. If a measure was sampled more than once (within and/or across experimental years), assessment time was included as a main effect and treated as a repeated measure, using the unstructured covariance structure type. Tukey-Kramer groupings at α=0.05 were used for comparing means.

In Experiment 1 at VA07, taproot cutting was not followed by ploughing in summer-renewed plots due to an error. Therefore, this site was analysed separately while TI07 and TR07 were analysed together, with site as a main effect (i.e. fixed).

3. Results

3.1 Renewal time

Summer renewal resulted in a higher dock density (Appendix B–D; Figure 1A, B) than spring renewal at all sites (VA07, TI07, TR07 and TI08) – both seed and root dock plants (Figure 2) – and in more dock biomass at VA07 (Figure 3). However, in Experiment 1 there were significant interactions between renewal time and assessment time ($P<0.0001$; Appendix B): increases in dock densities at TI07 and TR07 in the establishment year were mostly gone by the end of year 2 (Figure 1A). At VA07 and TI07, summer renewal also reduced crop coverage (Appendix B; data not shown). The crop and non-dock biomass was smaller at all sites following summer renewal compared to spring renewal (Appendix B–C, Figure 4); however, this does not include the harvest taken prior to summer renewal. Summer renewal proved superior to spring renewal only in terms of higher crop coverage at TR07 (Appendix B: data not shown) and lower total weed coverage at TI08 (Appendix C; data not shown).

3.2 Companion crop

Adding spring barley as a companion crop often reduced the dock population, but the effect differed between sites (VA07, TI07 and TR07). At VA07 the companion crop had no significant effect on the dock density or the crop and non-dock biomass or crop coverage (Appendix B), but it tended to reduce the dock biomass ($P=0.08$; Figure 3). At TI07 and TR07 there were fewer docks with a companion crop following summer renewal (Figure 1A, Appendix B: RT*CC, $P=0.05$); primarily dock root plants (Figure 2A, Appendix B: RT*CC, $P=0.03$), but there were also fewer seed plants at TI07 when following summer renewal and at TR07 when following spring renewal (Appendix B: Site*RT*CC; $P=0.03$). Dock biomass was also lower with a companion crop at TR07, and following summer renewal at TI07 (Figure 3, Appendix B: Site*RT*CC, $P=0.007$). At both TI07 and TR07, the crop and non-dock weed biomass was lower with a companion crop in the first year after spring renewal, but not in the second year, and not after summer renewal (Figure 4, Appendix B: RT*CC*Time, $P=0.005$). Plots with a companion crop had higher total crop coverage than the ones without a companion crop (71 vs. 34%) at both TI07 and TR07, but the difference was greater when spring renewal was used and it was greater at TR07 than at TI07 (Appendix B; data not shown).

3.3 False Seedbed

Effect of false seedbed on dock populations, tested at TI08, was strongly dependent on renewal time (Appendix C). After summer renewal, a false seedbed reduced dock density (Figure 2B), particularly seed plants (71% lower; Figure 2B). It also reduced the total weed coverage from 55 to 19% and increased the crop coverage from 28 to 43% (data not shown). After spring renewal, false seedbed instead increased dock density (Figure 1B) and decreased the crop and non-dock weed biomass by 45% (Figure 4), the crop coverage from 38 to 30%, while increasing the total weed coverage from 37 to 68%. Over both renewal times, a false seedbed led to more dock biomass (Figure 3, Appendix C: P=0.006).

3.4 Taproot cutting in conjunction with ploughing

Cutting the taproot in conjunction with ploughing had a weak and inconsistent effect on weeds and crop. There was no significant effect on the total number of dock plants at any of the tested sites (VA07, TI07, TR07, TI08 and MY09). In the summer-renewed plots at VA07, taproot cutting resulted in a large increase in root plants (2.3 vs. 0.5 plants m^{-2}; Appendix B: RT*Cut, P=0.003), but also an increase in crop and non-dock biomass and crop cover (Appendix B: RT*Cut, P=0.04 and P=0.03, respectively). Note that VA07 was the site where, due to an error, summer-renewed plots with taproot cutting were not ploughed. At TI07, taproot cutting combined with summer renewal resulted in a lower dock biomass (Appendix B: Site*RT*Cut, P=0.02) and increased crop coverage (Appendix B: Site*RT*Cut, P=0.05). At TR07, however, it was instead spring renewal combined with taproot cutting that resulted in less dock biomass (Appendix B: Site*RT*Cut, P=0.02) and increased crop and non-dock biomass (Appendix B: Site*Cut*CC, P=0.04), while combining taproot cutting with summer renewal instead lowered crop coverage (Site*RT*Cut, P=0.05). At TI08, taproot cutting did not affect the dock population or the crop (Appendix C). At MY09, taproot cutting tended to increase dock biomass when ploughing was performed at 16 cm, but had no effect with 24 cm ploughing (Appendix D: P=0.08). Note that taproot cutting was less even at 16 cm than at 24 cm due to technical problems.

3.5 Ploughing depth and skimmer

Ploughing depth and the use of a plough skimmer was tested at MY09. 24 cm ploughing reduced dock root plant density compared to 16 cm ploughing (Appendix D; P=0.04), but the effect was not apparent until the second post-treatment assessment (Figure 1C). Using a skimmer on the plough tended to further reduce dock density (Figure 1C, Appendix D: P=0.09) and dock biomass (P=0.08; data not shown).

4. Discussion

Renewal time strongly affected dock emergence, and influenced the efficacy of the tested management techniques. However, there was no support for the hypothesis that grassland renewal in summer would result in fewer seed plants than renewal in spring. Summer renewal resulted in both more seed and root plants than spring renewal (Figure 1A, B, Figure 2). Lie (2009) found that *R. longifolius* has a similar germination pattern as other *Rumex* species, so the fact that *R. longifolius* was prevalent at the study sites probably did not unduly influence the results. Rather it seems more likely that the greater number of dock plants following summer renewal was because the docks that germinated in summer encountered less competition from the crop. Since the crop is best adapted for spring sowing, and delayed sowing of grassland generally gives smaller yield in Norway (Skjelvåg, 1970), sowing in summer may have resulted in a less competitive crop. This is supported by our finding that the companion crop suppressed dock populations more following summer renewal than spring renewal, particularly at TI07 (Figures 1–3). Increased emergence of root plants after summer renewal agrees with studies showing that taproot regeneration can occur after soil disturbance in summer (Weaver and Cavers, 1979), or even autumn (Zaller, 2004). Similar to the findings of Harrington et al. (2013), our results indicate that seed plants are far more plentiful than root plants following grassland renewal, regardless of renewal time (Figure 2). However, given that dock densities in the second year was similar regardless of renewal time (except at VA07) indicates that the increased germination rate did not necessarily result in an increased survival rate.

An overall reduction in dock biomass and numbers when using a companion crop supported the hypothesis that a companion crop would reduce the number of dock seed plants, though the effect was not exclusive to seed plants. The companion crop appeared to be more suppressive following summer renewal than spring renewal. This could be due to a number of factors. First, the effect of the companion crop is likely to depend on the establishment of the grassland crop. The spring-renewed grassland crop may have been sufficiently competitive to outcompete the weak seed plants and the weakened root plants. Second, studies indicate that early growth is more influenced by root than shoot competition for *R. crispus* (Pye, 2008), *R. obtusifolius* (Jeangros and Nösberger, 1990) and *R. longifolius* (Haugland, 1993). Since all fertiliser was applied in spring, there would be more nutrients available to the dock plants that germinated in spring than those that germinated in summer. How fertilization influences the competitive ability of docks is not completely clear, however. For example, Pye (2008) found that fertilisation rates had little effect on the competition between *R. crispus* seedlings and a dense *Lolium perenne* sward, whilst other work has shown that higher fertilisation rates (adding slurry, or adding mineral fertilizer in addition to the slurry) benefit populations of *R. obtusifolius* (Hopkins and Johnson, 2002) and *R. crispus* (Mikulka and Kneifelová, 2004). Barley, with its deep root system, would be better at taking advantage of the reduced nutrient availability in summer than the grassland species would.

As expected, the false seedbed did not affect the number of root plants. Instead it may have assisted in their recovery after ploughing as the false seedbed increased dock biomass. On seed plants, the effect of a false seedbed was greatly dependent on renewal time. The hypothesis that a false seedbed would lower the number of seed plants was only supported when it followed summer renewal. When following spring renewal, the false seedbed tended to increase dock abundance and resulted in a reduced crop and non-dock weed biomass in the following year. One potential explanation is that a false seedbed results in a sowing delay of several weeks. This delay is likely to have been more detrimental to the crop's establishment following spring renewal, than summer renewal, as the summer renewal was already in a sense "delayed". Our results can be contrasted with Harrington et al. (2013), who reported that a 2-week fallow period after ploughing reduced dock coverage, at two different renewal times, but that a 4-week fallow did not cause further reduction. Another relevant factor, is that the effect of the false seedbed's harrowing is weather dependent. The weather data (Appendix E) show that in the spring-renewed plots, there was consistent precipitation during approximately the first week of harrowing and, perhaps more importantly, there was much precipitation in the days after the harrow period was finished. Thus, more germination may have been stimulated by abundant moisture, whilst damaged plant parts may have been aided in their recovery. For example, Boyd and Van Acker (2003) found that seedling emergence of *R. crispus* was most abundant when seeds were at the soil surface and soil moisture was at field capacity. In comparison, in our study there was a small amount of rain interspersed between the days (for example, maximum 7 mm on one day) in the summer-renewed plots, and perhaps even more crucially, there was no rain for about one week after the end of harrowing. The better nutrient availability in the spring-renewed plots may also have helped the dock plants recover better from the harrowing, as nitrogen application around the time of soil disturbance results in the greatest emergence of dock seedlings (Milberg, 1997; Lie, 2009). Thus, current results might have been different if the fertilizer had been distributed at intervals instead. This is a worthy future research topic.

There was no support for the hypothesis that cutting the taproots in conjunction with ploughing would reduce the number of root plants. In some instances, taproot cutting did reduce dock biomass and increase crop growth, but the effect was weak and inconsistent. Still, this shows that even if taproot cutting cannot reduce the number of emerged shoots, it can reduce their competitiveness. Conversely, the experiments also showed that if the ploughing depth is too shallow (16 cm) or ploughing is omitted (as was accidently done in summer renewal at VA07), taproot cutting can actually increase dock root plant abundance. In the case of shallow ploughing, this may have been due to the less even root cutting at 16 cm than at 24 cm. However, a study by Pye et al. (2011) gave similar results, as severed *R. crispus* root necks showed greater biomass and seed production than those from intact roots. Pye (2008) suggested that the reason was greater shoot initiation caused by fragmentation, with shoot survival being dependent on sufficient soil nutrient levels. Kolberg et al. (2018) proposed a similar theory for *E. repens*, as rhizome fragmentation did not reduce biomass acquisition under favourable nutrient conditions. An accelerated regeneration rate following fragmentation may allow docks and other perennial weeds to gain an inter-species competitive advantage. However, if there was a large difference in nutrient availability between spring and summer renewal (as we have posited, but not measured), then our study does not provide support for the theory that nutrient availability has a vital influence on taproot regeneration after fragmentation. Our results are also comparable to those of Andersson (2007), who concluded that shallow tillage (5-8 cm depth) prior to ploughing did not reduce the total density of established dock plants in comparison to deep ploughing alone.

One potential reason for the poor results from the taproot cutting may be that it was performed in conjunction with ploughing. It may be better to cut the taproots in advance of ploughing, let them re-shoot, and then plough them down. Taproot cutting could even be performed in late autumn, so that the taproot fragments are weakened or killed by winter conditions. The weight loss of perennial weed's storage organs due to respiration can be large during winter (Verwijst et al., 2013), so losing a large proportion of root biomass prior to winter may increase dock vulnerability in spring. Another reason that taproot cutting had such a poor effect may be that the cutting techniques used need more refinement. The modified skimmer used at TI08, for example, did not quite manage to cut along the entire furrow breadth as intended.

There was weak support for the hypotheses that attaching a skimmer to the plough, and ploughing deeper (24 vs 16 cm), would result in fewer root plants. The difference was not very strongly significant for either method, but that is most likely because it was only investigated at one site. The effect may also have been stronger if a grass crop had been sown in the experiment. Moreover, even ploughing at 16 cm without a skimmer caused a substantial reduction in dock root density compared to pre-renewal levels (Figure 1C). Pino *et al*. (1995) showed that *R. obtusifolius* can reshoot from 20 cm depth, but not from 30 cm. The results of our study indicate that the same is true for *R. longifolius*. The addition of a skimmer to the plough appears to improve the efficacy of the ploughing results, regardless of ploughing depth.

4.1 Implications for control of docks during grassland renewal

In our experiments, the best non-chemical way to suppress dock emergence following grassland renewal was to perform high-quality ploughing and to provide favourable establishment conditions for the new grassland crop. Very few root plants survived ploughing, even at 16 cm depth, and 24 cm ploughing with a skimmer pushed the number very close to zero, even without a sown crop. This is consistent with the findings of Pino et al. (1995) and Gummesson and Svensson (1973), respectively, and thus suggests that the results are valid beyond the conditions prevailing in the current study. Though, local conditions may necessitate modifications. Since dock seed plants emerge in great numbers after ploughing, regardless of renewal time, the best time for dock control most likely coincide with whatever time is best for establishing a competitive crop. A companion crop generally increased the suppressive effect on the dock population, though its effect likely depends on how well the grassland crop establishes. A weak grassland crop benefits more from a companion crop than a competitive one. A trade-off was that the companion crop also competed with the grassland crop, which in the case of spring renewal resulted in a reduced harvest yield in the establishment year, but not in the subsequent year (Figure 4). Since companion crops usually increase the overall harvestable yield in the establishment year (Skjelvåg, 1970) and the companion crop significantly increased crop coverage, this would indicate that the reduction was primarily in the weed proportion of the harvested biomass. Based on the present results, it can be concluded that there is plenty of room to experiment with locally adapted establishment methods and grassland mixtures to reduce dock establishment and growth by improved crop competitiveness.

Our results did not suggest that taproot cutting and false seedbeds, as practiced in this study, are effective. This does not exclude, though, that taproot cutting might have a potential, if further developed, perhaps as part of a long-term starvation strategy before sowing. However, in agreement with what is already known about starvation strategies (Håkansson, 2003), the results from this study indicate that taproot cutting should be followed up by deep ploughing to prevent increased proliferation. False seedbeds appeared to be quite problematic, producing very variable results. However, other studies have produced more promising results (e.g. Harrington et al., 2013). Thus, the false seedbed method has to be studied in greater detail to identify conditions that may give favourable results.

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Figure texts

Figure 1. Mean number of *Rumex* plants (back-transformed means except the first sampling) through the experimental period for Experiment 1 (A), Experiment 2, i.e. trial TI08 (B) and Experiment 3, i.e. MY09 (C). The first sampling (i.e. Year 1/spring) was taken before treatments were applied. The exact assessment dates are given in Table 2. Note that in Experiment 3 no crop or fertilizer was added. CC = companion crop; FS = false seedbed.

Figure 2. Mean numbers (back-transformed means) of *Rumex* root plants and seed plants assessed in Year 1 (cf. “Time 1” in Table 2) in Experiment 1 (A) and Experiment 2, i.e. trial TI08 (B). Means with the same letter of the same type are not significantly different for Tukey-Kramer groupings at α=0.05; the letters are divided into three types (upper-case,

lower-case and lower-case with asterisk) since the data was analysed in three different models (see section 2.4). CC = companion crop; FS = false seedbed.

Figure 3. Mean aboveground *Rumex* biomass (back-transformed means) per trial and year. Means with the same letter of the same type are not significantly different for Tukey-Kramer groupings at α=0.05; the letters are divided into three types (upper-case, lower-case and lower-case with asterisk) since the data was analysed in three different models (see section 2.4).CC = companion crop; FS = false seedbed.

Figure 4. Mean combined biomass of main crop, companion crop (only in companion crop treatments and only in year 1, i.e. the renewal year) and non-dock weeds per trial and year. Means with the same letter of the same type are not significantly different for Tukey-Kramer groupings at α=0.05; the letters are divided into three types (upper-case, lower-case and lower-case with asterisk) since the data was analysed in three different models (see section 2.4). Please note that mean values are of dry weight for trials VA07, TI07 and TI08, but fresh weight for trial TR07. CC = companion crop; FS = false seedbed.

Table 1 Trial site details. pH and nutrient availability (K-AL, P-AL, Mg-AL, Ca-AL as mg/100g) were measured after the experiments: TI07 and TI08 in 2009, VA07 and MY09 in 2012.

Experiment	Trial ID	Location	Renewal year	Management	Lat., Long.	m above sea level	Soil type	pH	K-AL	P-AL	Mg-AL	Ca-AL	*Rumex* species
1	TI07	Tingvoll	2007	Organic	62°55′N, 8°11’E	17	Silty sand	5.9	7	21	5	103	*R. longifolius* *R. obtusifolius* *R. crispus*
	VA07	Valdres	2007	Conventional	61°7′N, 9°3'E	710	Medium sandy loam, stone rich	6.6	8	8	26	190	*R. longifolius*
	TR07	Tromsø	2007	Conventional	69°34′N, 18°36′E	11	Well humified, drained peat soil	-	-	-	-	-	*R. longifolius*
2	TI08	Tingvoll	2008	Organic	62°55′N, 8°11’E	41	Loam	5.8	15	13	6	52	*R. longifolius* *R. obtusifolius* *R. crispus*
3	MY09	Mysen	2009	Organic	59°34′ N, 11°20′E	150	Clay loam	6.7	35	6	24	220	*R. longifolius*

Table 2 Management and sampling dates of the three experiments at the four sites. Grassland renewal was performed in the first year of the experiment. Except for Experiment 3, sampling was conducted in both the establishment year and the year after establishment

		Experiment 1						**Experiment 2**		**Experiment 3**
		Valdres 2007 (VA07)		**Tingvoll 2007 (TI07)**		**Tromsø 2007 (TR07)**		**Tingvoll 2008 (TI08)**		**Mysen 2009 (MY09)**
		Spring ploughing	**Summer ploughing**	**Spring ploughing**	**Summer ploughing**	**Spring ploughing**	**Summer ploughing**	**Spring ploughing**	**Summer ploughing**	**Spring ploughing**
Taproot cutting		20 May	30 July	29 April	27 June	11 June	16 July	30 April	4 June	-
Ploughing & harrowing		20 May	30 July	29 April	27 June	11 June	16 July	30 April	4 June	5 May
Sowing		24 May	2 August	4 May	2 July	12 June	16 July	9 May | 6 June*	5 | 25 July*	-
False seedbed harrowing		-	-	-	-	-	-	23, 30 May, 6 June	12, 18, 25 July	-
Dock density sampling	**Time 0**	18 May		28 April		11 June		29 April		5 May
	Time 1 (Root | seed)	4 | 11 June	29 August | 4 September	19| 19 June	14 | 14 August	20 | 20 June	28 | 28 June	24 June, 18 July | 24 June, 25 July*	12 August, 5 September | 19 August, 11 September*	21 May
	Time 2	9 October		15 October		21 September		21 April		27 May
	Time 3	26 May		1 April		12 June		26 June		10 June
	Time 4			1 September		21 August		7 September		25 June
Plant biomass sampling	**Year 1**	8 June		13 September	20 September	31 July	30 August			25 June
	Year 2			16-18 June		30 July		5 June		
Vegetation coverage sampling	**Year 1**	9 June		19 June	14 August	21 September		24 June, 25 July*	19 August, 11 September*	-

*Later sowing and sampling dates for treatment combinations with false seedbed

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