Weekly defoliation controls, but does not kill broad-leaved dock (Rumex obtusifolius)

F K VAN EVERT*, M COCKBURN†, J E BENIERS* & R LATSCH†

*Agrosystems Research, Wageningen University & Research, Wageningen, The Netherlands, and †Agroscope, Competitiveness and System Evaluation, Ettenhausen, Switzerland

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Summary

Broad-leaved dock (Rumex obtusifolius L.) is a troublesome weed that predominantly grows in pastures and grassland. We hypothesised that frequent defoliation of Rumex will, over time, result in a reduction in root weight and leaf area, to the point where the impact on grass production is negligible. In order to investigate this hypothesis, we conducted three experiments. The objective of the first experiment was to perform a preliminary test of the hypothesis, using potted plants growing in the controlled conditions of a glasshouse. This experiment showed a rapid decline in leaf growth in plants that were defoliated weekly. The objective of the second experiment was to test the hypothesis in realistic outdoor conditions while still being able to collect detailed plant growth information. This experiment confirmed the findings of the glasshouse experiment and provided evidence that leaf growth ceased as a result of a dwindling supply of carbohydrate reserves in the root. Defoliated plants did not exhibit increased mortality. Finally, the objective of the third experiment was to test the hypothesis in a commercial pasture where normal field operations, specifically grass harvesting (three times) and slurry injection (twice), were performed. The results of this experiment were consistent with the results of the other two experiments. We conclude that weekly defoliation, maintained for three or more months, is an effective method to control (reduce the impact on grass production), but not kill, R. obtusifolius in pasture.

Keywords: mechanical weed control, compensation point, robot, below-ground biomass.

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Introduction

Broad-leaved dock (Rumex obtusifolius L.) is a troublesome weed that predominantly grows in pastures and grassland. If left uncontrolled, Rumex plants reach a high density and can reduce grass productivity by 10–40% (Oswald & Haggar, 1983; Courtney, 1985; Sobotik, 2001). When consumed in large quantities, Rumex may form a threat to livestock health (Zaller, 2004).

It is difficult to eliminate Rumex from pastures. The plant spreads easily because it produces a large number of seeds, which are dispersed by wind, water and animals; thus, grassland may become infested from adjacent fields or unmanaged areas. Seeds can remain viable in the ground for decades (Cavers & Harper, 1964; Foster, 1989). Germination of Rumex seeds is induced by exposure to light, so pastures damaged by intensive use or drought offer ideal conditions for the establishment of Rumex (Mikulka & Kneifelova, 2004). The presence of Rumex can be considered an indicator of poor agricultural management (Zaller, 2004). The roots of Rumex can grow up to 2 m deep
(Sobotik, 2001) and thereby reach nutrients and water which are out of reach of plants with shallower root systems. Rumex produces a large taproot, which serves as storage for carbohydrate and can support regrowth when the above-ground parts have been damaged.

Given the near impossibility of permanently eliminating the weed, it has been stated that the aim of Rumex control is ‘to hinder the build-up of seeds and to weaken their regrowth capacity by removing or destroying their above- and below-ground biomass’ (Zaller, 2004) and thus limit the negative impact of Rumex to an acceptable level. ‘Acceptable’ is not well-defined but organic dairy farmers in the Netherlands consider a density of up to 1,000 plants ha$^{-1}$ acceptable (Van Evert et al., 2011). We define as acceptable a Rumex population that has only a small impact on grass productivity, that produces no more biomass than can be safely ingested by livestock, and that produces no seed.

Many Rumex control methods have been evaluated. These include the application of systemic herbicides (Brock, 1972; Savory & Soper, 1973) or selective herbicides such as MCPA. The latter herbicide will kill Rumex seedlings, but it has less effect on mature plants because the herbicide is not translocated into the root system. The treatment must be repeated in subsequent years to be effective. An effective, non-chemical way to control Rumex is to dig out the taproot to a depth of 0.15 m (Zaller, 2004; Hujerova et al., 2016). Although this procedure presents a high success rate of 90% (Roy Latsch, Agroscope, unpublished data), it is very labour-intensive. Effective methods aimed at damaging or removing the taproot include microwaves (Latsch et al., 2007), chopping (Van Evert et al., 2011), treatment with a hot steel rod (Bond et al., 2003) and the application of hot water to the roots (Latsch & Sauter, 2014; Latsch et al., 2016). Mowing or cutting can be used to control Rumex (Courtney, 1985; Stilmant et al., 2010). However, production grassland is seldom mowed more frequently than once every 6 weeks and this is not sufficiently frequent to control Rumex. Grazing has been reported to be an effective way to control Rumex (Hejcman et al., 2014). The efficacy of grazing depends on the soil, the development stage of the Rumex plant and the animal species used (Pavlů et al., 2006; Hejcman et al., 2014). Finally, the need for Rumex control can be reduced by reducing the Rumex population during grassland renewal (Ringelle et al., 2019).

Several efforts have been made to develop robotic weeding for Rumex by automating one of the above-mentioned control methods. The robot of Van Evert et al. (2011) uses a chopping mechanism to destroy the taproot to a depth of 10–20 cm. This is effective but prone to mechanical failure in dry or stony soil. In the DockWeeder project, the hot water method of controlling Rumex (Latsch & Sauter, 2014; Latsch et al., 2016) was automated (http://dockweeder.eu/ and http://ict-agri.eu/node/35755). Both methods target the taproot and consume a large amount of energy; the hot water robot additionally needs to transport a large amount of water. In both cases, targeting the taproot resulted in a heavy, expensive and, ultimately, impractical robot.

In contrast to the methods mentioned above, defoliation of a single Rumex plant (‘selective weeding’) does not require a large amount of energy. Following defoliation, Rumex will produce new leaves by using energy reserves from the taproot. This leads to a decrease in the weight of the taproot. At some point in time, the rate of assimilation by the newly formed leaves will start to exceed the rate of respiration and from then on plant weight will increase. This is called the compensation point (CP). If one were to defoliate a plant repeatedly before the compensation point was reached, a continuous decline in plant weight could be expected. This will, over time, result in death of the weed plants. Defoliation of a single plant can be achieved with, for example, a small mower which can be mounted on a small robot. Rumex has a large capacity to regrow from its taproot, and thus, defoliation will have to be repeated multiple times in order to have significant effect on the weed. Such multiple defoliations are in principle entirely practical if a robot is available for this task.

The effect of frequent defoliation of Rumex has been addressed in only a few studies. In a glasshouse experiment, five weekly defoliations resulted in a decrease in the total non-structural carbohydrate (TNC) content of potted Rumex plants from 38% at the start of the experiment to 3% at the end (Hidaka, 1973). In the field, mowing 5–7 times per season during a period of 6 years reduced the abundance of Rumex by 60% (Courtney, 1985). In another field experiment, Rumex plants were removed, by digging to 5 cm below soil surface, 2 or 3 times per year (a total of 8 times) during three consecutive growing seasons; in addition, the grassland was cut twice per year. In this experiment, no significant decrease in the density of Rumex was recorded (Strnad et al., 2010). In an extensive review of the literature, it was concluded that biweekly defoliation will be needed to control Rumex (Zaller, 2004).

The paucity of data describing the response of Rumex to frequent defoliation, especially in field conditions, means that at present it is not possible to devise an optimal defoliation strategy to control Rumex. Questions that need to be answered include the following: Can the large effect of weekly defoliations observed in the glasshouse be extrapolated to field...
conditions? What is the effect of different defoliation frequencies? Should subsequent defoliations be evenly spaced in time? Will the plant enter a rest phase and thus escape defoliations? Will the plant modify its growth form? Is regrowth limited only by the availability of carbohydrate reserves? How does the availability of water and nutrients interact with availability of carbohydrate reserves? In the future, we aim to construct a robot that uses frequent defoliation to control *Rumex* and then use the robot to evaluate the above questions in practical conditions in multi-year, on-farm experiments. Before spending effort on building a robot, we need to demonstrate that frequent defoliation is viable at least in principle. We hypothesised that weekly defoliation will exhaust the carbohydrate reserves in the taproot of *Rumex* and that this will limit regrowth of leaves to a point where the impact of the weed on grass production is of no concern in farming practice. In order to investigate this hypothesis, we conducted three experiments. The objective of the first experiment was to confirm the results of Hidaka (1973), using potted plants growing in the controlled conditions of a glasshouse. The objective of the second experiment was to test the hypothesis in realistic outdoor conditions while still being able to collect detailed plant growth information. Finally, the objective of the third experiment was to test the hypothesis in a commercial pasture where normal field operations were performed.

**Materials and methods**

**Experiment 1 (Glasshouse experiment)**

The roots of twenty plants were dug up on 4 July 2016 on an abandoned plot near Wageningen, the Netherlands. The leaves were removed by cutting the petioles close to the soil with pruning scissors and discarded. The roots were gently washed, dried with paper towels and weighed. On the following day, each root was planted in a pot containing 5.4 kg artificial soil (70% quartz sand, 18% crushed hydro-grains and 12% clay powder/kaolin) upon the recommendation of Seinhorst et al. (1995). The surface of the pot was covered with a plastic sheet to limit evaporation. The sheet had a single opening in the centre, allowing sprouts to emerge. The pots were placed in a glasshouse; climate details are given in Table 1. Pots were watered two times per week to maintain soil moisture content between 10% and 15% (volume). The location of the pots in the glasshouse was changed each time after weighing to achieve homogeneous growing conditions. The roots were sorted by initial weight and then assigned alternatingly to one of two treatments: control or defoliation. Plants in the control treatment grew undisturbed during the entire experiment, whereas the leaves of plants in the defoliation treatment were removed once a week, with pruning scissors, by cutting slightly above soil level, with the first defoliation occurring 14 days after the beginning of the experiment. Cut leaves were oven-dried and weighed. The experiment was terminated after 112 days. At that time, all plants were dug up. The leaves were removed, oven-dried and weighed. Roots were cleaned, dried with paper towels and weighed fresh. Subsequently, the roots were cut, oven-dried and weighed again.

**Experiment 2 (Field experiment)**

The field experiment was conducted in Tänikon, Ettenhausen, Switzerland. Tänikon is located 540 m above sea level and has an average annual precipitation of 

| Glasshouse experiment | Field experiment | Farm experiment |
|-----------------------|------------------|-----------------|
| \( T_{\text{mean}} \) °C | \( T_{\text{mean}} \) °C | Precipitation mm | Irradiation MJ m\(^{-2}\) day\(^{-1}\) | \( T_{\text{mean}} \) °C | Precipitation mm | Irradiation MJ m\(^{-2}\) day\(^{-1}\) |
| April 18.0 | 7.7 | 138 | 16.6 | 8.0 | 33.5 | 13.7 |
| May 18.0 | 14.2 | 85.9 | 21.8 | 14.8 | 32.4 | 18.8 |
| June 18.0 | 19.4 | 68.8 | 24.1 | 17.8 | 56.8 | 18.8 |
| July 18.0 | 19.0 | 184.1 | 21.0 | 17.9 | 105.2 | 18.0 |
| August 18.0 | 18.8 | 112.9 | 19.0 | 17.1 | 88.5 | 15.1 |
| September 18.0 | 12.6 | 136.5 | 12.6 | 13.5 | 103.2 | 10.6 |
| October 18.0 | 10.8 | 66.4 | 9.8 | 12.8 | 61.5 | 5.9 |
| November 18.0 | 4.8 | 119.8 | 3.7 | 6.7 | 77.5 | 2.8 |

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1200 mm. The soil texture at this site consists of clay loam with 35% clay, 34% silt and 31% sand (nomenclature according to AG Boden, 1994). The soil type is Cambisol (according to Iuss Working Group, 2014).

On 16 May 2017, 300 Rumex plants were dug up from a permanent grassland site. After removing the leaves, the roots were carefully washed and dried. Long roots were shortened to a length of 0.3 m and weighed. On the same day, the roots were planted on an extensive grassland site on the Tánikon farm.

To ensure ideal sprouting conditions, with a good soil contact, the roots were watered. According to Roberts and Hughes (1939), it takes approximately 25 days after defoliation for Dock plants of these species (R. obtusifolius, R. crispus) to start gaining in weight; therefore, the test plants grew undisturbed for 4 weeks. During this period, the test field was occasionally watered to support root proliferation. During the experimental period, both Koubachi Plant Sensor 2 (Koubachi AG, Zürich, Switzerland) and Sentek™ Drill & Drop Probe (Sentek Pty Ltd, Stepney, Australia) sensors recorded soil moisture. Unfortunately, soil moisture recordings were inconsistent, resulting in data gaps. A meteorological station located in about 100 m distance provided weather data. Details on the weather conditions during the experiment are given in Table 1.

Roots were planted in a quadratic grid with 1 m distance between each plant, where ten plants formed one row. The test site therefore included a total of 30 rows. Roots were numbered consecutively within the plot, grouped in five weight classes of 60 plants each from light (A) to heavy (E) (Table 2) and subsequently randomly assigned to one of two treatments: control and defoliation. Then, five plants of each treatment, including weight classes A-E, were randomly assigned to a harvest date.

Plants in the control group were left to grow undisturbed until the day they were harvested. Plants in the defoliation treatment were defoliated every 7 days, beginning on 14 June 2017. The number of leaves, the fresh weight of leaves and leaf area were recorded. Leaf area was measured with a Portable Area Meter (LI-3000A Portable Area Meter with LI-3050A Transparent Belt Conveyer, LI-COR, Inc., Lincoln, Nebraska, USA). Leaves were oven-dried at 105°C in order to record dry matter.

On each harvest day, five plants of the control treatment and five plants of the defoliation treatment were removed from the soil. After washing and drying the taproot, their fresh matter and dry matter weights (dried at 105°C) were determined. Leaf area, number of leaves and leaf fresh matter and dry matter were recorded for all plants.

The last harvest was performed on 25 October 2017. The experimental plot was not disturbed during the winter. On 7 May 2018, for each of the plants that had not been removed from the soil in the course of the experiment, the plants’ regrowth in the form of one or more (possibly small) green leaves was determined. If any regrowth occurred, we considered plants alive, whereas we considered them dead when no regrowth occurred.

### Experiment 3 (Farm experiment)

The farm experiment was performed on a 4 ha field with sandy soil of an organic dairy farm in Bennekom, the Netherlands. It has a higher elevation than surrounding fields and, according to the farmer, often suffers from drought in July or August. However, in very wet conditions it has higher productivity than surrounding fields. In March, chicken manure was applied at a rate of 7 t ha⁻¹; cattle slurry was injected on 30 May (15 m³ ha⁻¹) and 18 August (10 m³ ha⁻¹). Details on the weather conditions during the experiment are given in Table 1.

On 4 May 2017, 93 Rumex plants were selected by walking in a straight line through the field and tagging individual plants. Mature Rumex plants begin to fragment their taproots after 3 years and therefore often grow in clonal clusters (Bond et al., 2007). We selected only single, free-standing plants. Plants were numbered in the order in which they were selected and tagged with a small wooden marker that was put into the ground. The coordinates of each plant were determined using RTK-GPS (HiPer Pro, Topcon, Tokyo, Japan) so that plants could be revisited even if markers were lost.

We consecutively assigned three plants to a group (31 groups in total). Within a group, plants were randomly assigned to one of three treatments: start, control and defoliation. On 8 and 9 May, plants in the start treatment were removed from the soil. They were cleaned, separated into above- and below-ground parts, dried and weighed, to obtain the weight of the roots at the start of the experiment. On the same day, plants in the defoliation treatment were defoliated. Plants in the control treatment were left untouched until 5 September, the last day of the experiment.

### Table 2 Field experiment. Descriptive statistics of the five classes of initial fresh root weight (g)

| Weight classes | A   | B   | C   | D   | E   |
|----------------|-----|-----|-----|-----|-----|
| Min            | 8.2 | 25.0| 42.0| 66.4| 106.9|
| Max            | 24.5| 41.6| 65.9| 106.3| 253.3|
| Mean           | 17.1| 32.2| 54.4| 83.0| 162.7|

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Starting on 23 May, plants in the defoliation treatment were defoliated once a week with the exception of three dates on which the field had just been mowed by the farmer (15 May, 10 July, 14 August). Removed leaves were collected, oven-dried and weighed. On the last day of the experiment, plants in the control and defoliation treatment were removed from the soil, cleaned, separated into above- and below-ground parts, oven-dried and weighed (in the same way as the plants in the start treatment on the first day of the experiment).

Data analysis and statistics

All data analyses were performed in R version 3.5.1 (R Core Team, 2018).

For the glasshouse and farm experiments, we used one-way ANOVA to evaluate the significance of differences in root weight between treatments.

For the field experiment, a linear mixed-effects model was fitted in which the difference of root weight dry matter of defoliated plants was used as the response variable, whereas the cumulative leaf weight (continuous), leaf count (continuous) and the week of experiment (continuous) were used as fixed effects. The model included mean daily temperature and cumulative rainfall as crossed random effects. Due to a lack of repetition, we did not include weight groups in the model. The model was fitted using the lmer function in R (package lme4, Bates et al., 2015). After fitting the model, we visually checked the residuals for normal distribution and homogeneity of variance. Consequently, to fulfil these assumptions we removed five outliers from the dataset.

The dredge function (package MuMIn) was used to select the best model among all possible combinations of fixed effects, based on the smallest Bayesian information criterion (BIC) and the largest model weight ($w_i$). The model weight $w_i$ informs on the probability of the selected model to be optimal compared with the other tested models given the data, where all possible models $w_i$’s add up to 1 (Symonds & Moussalli, 2011).

We tested the model described above, as well as all smaller models, including the null model (model without fixed effects). This is an alternative approach to frequentist $P$-value based testing, and therefore, no $P$-values are presented.

Results

Glasshouse experiment

All but one of the transplanted roots developed vigorous leaf growth within 2 weeks of planting. In the control treatment, leaf production continued during the entire experiment (plants were not harvested, but a visual assessment was made). In the defoliation treatment, the rate of leaf production decreased with time during the experiment (Fig. 1). By the end of the experiment, production of leaves had ceased entirely in 6 out of the 10 plants in the defoliation treatment.

In the control treatment, the mean fresh root weight increased from 34.4 ± 21.9 g at the start of the experiment to 145.2 ± 54.6 g at the end; in the defoliation treatment, mean fresh root weight decreased from 38.6 ± 27.7 g to 33.9 ± 36.1 g. The large standard deviations are caused by the large variation in initial root weight, rather than by measurement uncertainty. At the start, there was no difference in fresh root weight between treatments ($P = 0.7112$), at the end the difference was significant ($P = 0.00016$). At the end of the experiment, mean dry root weight in the control treatment was 56.0 ± 27.2 g and in the defoliation treatment it was 7.0 ± 5.9 g (a significant difference, $P = 0.00056$). Dry matter fraction of the roots was 0.39 in the control treatment, and it was 0.21 in the defoliation treatment.

Fig. 1 Glasshouse experiment. Weekly production of leaf dry matter by plants in the defoliation treatment, as a function of days from start of the experiment. Error bars indicate one standard error.

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The average dry weight loss of roots was 3.81 g plant\(^{-1}\), and the average cumulated leaf dry weight production was 1.78 g plant\(^{-1}\) (Table 3). In other words, for every g of taproot dry weight, 0.46 g of leaf dry matter was produced.

**Field experiment**

Plants in the control treatment exhibited healthy growth whereas plants in the defoliation treatment were severely impacted by the removal of leaves. In the defoliation treatment, the rate of leaf dry matter production dropped from approximately 1 g plant\(^{-1}\) week\(^{-1}\) to approximately 0.1 g plant\(^{-1}\) week\(^{-1}\). In the control treatment, plants were allowed to grow unimpeded from the start of the experiment until the moment of harvest. The amount of leaf dry matter harvested was the cumulative amount of dry matter produced until that moment. The cumulative leaf dry matter production varied between 3 and 5 g plant\(^{-1}\), with the higher numbers more frequently encountered during the later part of the experiment. Several other traits increased with time for control plants and decreased for defoliated plants. This was true for the number of leaves, leaf surface, the dry matter fraction of roots and, finally, root weight (Fig. 2). At the end of the experiment, the root weight of plants in the control treatment had increased by 76% while the root weight of the plants in the defoliation treatment had decreased by 30% (Table 3).

It is of interest to note that stable allometric relationships were found that hold across the control and defoliation treatments. Leaf dry matter weight, leaf surface and leaf count were highly correlated with leaf fresh matter weight.

In the defoliation treatment, the decrease in root weight over the course of the experiment can be explained by the cumulative leaf biomass production (\(w_i = 0.669; \text{BIC} = 52.9; \text{delta} = 0.00\)) (Fig. 3). The average dry weight loss of roots was 5.20 g plant\(^{-1}\), and the average cumulated leaf dry weight production was 4.39 g plant\(^{-1}\) (Table 3). This implies a value of 0.84 for the conversion factor.

### Table 3

| Experiment | Treatment | Root fresh weight (g) | Root dry weight (g) | FR End | Leaf dry weight (g) Cumulative |
|------------|-----------|-----------------------|---------------------|--------|------------------------------|
| Glasshouse | Control   | 34                    | 10                  | 56     | 5.81                         |
|            | Defoliation | 39                   | 11                  | 7      | 0.65                         | 1.78 |
| Field      | Control   | 59                    | 17                  | 29     | 1.76                         |
|            | Defoliation | 63                   | 18                  | 12     | 0.70                         | 4.39 |
| Farm       | Start     | 85                    |                     | 37     | 1.57                         |
|            | Control   |                       |                     |        |                              |
|            | Defoliation | 19                   | 0.78                |        |                              |

The length of the bars is one standard error and indicates the variation in the five plants that were harvested on each date (one plant from each initial root weight class).
For each harvested plant in the defoliation treatment, the fraction of dry root weight remaining was calculated as the dry weight of roots at a given point in time divided by dry weight of roots at the start of the experiment (Table 3). The amount of leaf biomass produced during the week preceding the harvest decreased as the fraction of dry root weight remaining decreased, that is as the root was being exhausted. Visual inspection of the data suggests that leaf production ceases when root dry weight has declined to 0.5–0.6 of the root dry weight at the start of the experiment.

There was no effect of treatment on the percentage of plants that exhibited regrowth after the winter. In the control treatment, 37 plants were not harvested during the experiment and remained in the field during the subsequent winter. In spring, 20 of these plants (54%) started to regrow. In the defoliation treatment, 26 out of 44 plants (59%) started to regrow.

**Farm experiment**

On the first day of the experiment, the average dry matter weight of leaves removed was 9.5 g plant\(^{-1}\). Two weeks later, at the first repeated defoliation, this was 1.9 g plant\(^{-1}\). At subsequent defoliations, 0.1 g plant\(^{-1}\) was frequently observed (Fig. 4).

The average dry matter weight of roots at the start of the experiment was 23.7 ± 15.3 g plant\(^{-1}\); at the end of the experiment, this number had increased to 37.3 ± 25.1 g plant\(^{-1}\) for the control plants and it had decreased to 18.6 ± 11.9 g plant\(^{-1}\) for the plants in the defoliation treatment. The difference in the root dry weight at the end of the experiment was significant (\(P = 0.00173\)).

The average dry weight loss of roots was 5.10 g plant\(^{-1}\), and the average cumulated leaf dry matter production was 4.96 g plant\(^{-1}\) (Table 3). This implies a value of 0.97 for the conversion factor. In this
experiment, there appeared to be no relation between initial root weight and leaf dry matter production.

Data from the three experiments are summarised in Table 3. On average, roots lost 35% of initial dry weight in the glasshouse experiment, 30% in the field experiment and 22% in the farm experiment.

Discussion

As a first step towards the construction of a robot that uses frequent defoliation to control *Rumex*, we have attempted to quantify a baseline response of *Rumex* to an aggressive, weekly defoliation regimen. To the best of our knowledge, this is the first report to describe weekly defoliation of *Rumex* maintained over a period of months.

Three experiments were carried out in very different environmental conditions. In each experiment, weekly defoliation during a period of 3 months or longer resulted in virtually complete cessation of leaf growth. In each experiment, the rate of leaf dry matter production declined rapidly during the initial weeks of the defoliation treatment and then remained low until the end of the experiment. Finally, root weight of defoliated plants declined by 42% in the glasshouse experiment, 37% in the field experiment and 22% in the farm experiment. These numbers are in line with the results from another defoliation experiment in *Rumex* where TNC content decreased from 38% to 3% (Hidaka, 1973). The range from 22 to 42% decline that we found can be explained as follows. In the glasshouse, optimal growing conditions existed and regrowth was vigorous; as a result, the roots were exhausted quickly. In the field and farm experiments, regrowth was likely limited by a lack of water during part of the growing season, as well as by interspecific competition; thus, carbohydrates reserves in the taproot were used less quickly and root weight declined less quickly as well.

The apparent efficiency for converting root dry matter into leaf dry matter was 0.46 in the glasshouse experiment, 0.84 in the field experiment and 0.97 in the farm experiment. There are several reasons that may explain these differences. First, in the glasshouse and field experiments, taproots were removed from the soil. After replanting, these roots expended energy to recreate a system of fine roots. These fine roots were discarded during the harvest. Second, in the field experiment the plants were exposed to higher light intensity and it can be expected that they were able to form more assimilates than in the glasshouse experiment. Third, in the farm experiment plants were left in the soil (they were not transplanted). The plants in this experiment did not have to expend energy on recreating fine roots. Also, when taproots were removed from the soil, inevitably some root parts were left in the soil, including portions of the taproot that were located deep in the soil and thus could not be removed, as well as secondary taproots and underground stems that were broken off the main root during digging. Thus, plants in the farm experiment were able to draw on resources that were larger than was determined by weighing the excavated roots in the start treatment. Fourth, in the farm experiment it was sometimes difficult to find the plants in the field; thus, on a number of occasions, a plant in the defoliation treatment escaped defoliation. This would have enabled this plant to produce more assimilates than the other plants in the treatment and also this may have contributed to the large value for the apparent conversion efficiency in the farm experiment.

It is possible that the rate of leaf biomass production was reduced in response to environmental stimuli: shortening of day length, reduced irradiation, lower temperature (Taab et al., 2018) or lack of nutrients (Hejcman et al., 2012). This was most likely not the case in our experiments because leaf growth ceased early in the experiments before day length, irradiation or temperature changed in a significant way; also, there was an ample supply of nutrients in our experiments. We conclude that the cessation of leaf growth in our experiments can be explained by depletion of TNC reserves in the taproot.

An interesting result is that the aggressive, weekly defoliation imposed in our experiments did not decrease winter survival rate. The ability of *Rumex* to survive various control strategies, even when continued over a period of years, had been noted (Courtney, 1985; Strnad et al., 2010; Hejcman et al., 2012) but our defoliation was considerably more aggressive than those used by other authors.

In practice, the aim of controlling *Rumex* is to limit damage caused by the weed to an acceptable level. The results presented in this paper suggest that frequent defoliation can be used to reach this aim. After two or three defoliations, the leaf area of the weed is so small that the competition with grass for light, water and nutrients would have a negligible effect on grass production. By the same token, the amount of leaf biomass is too small to cause animal health problems. Finally, the spread of *Rumex* is strongly reduced when the defoliation interval is short enough to prevent flowering and seed production, and when the growth rate of the weed is too small to allow for vegetative reproduction.

The large effect of the first two or three weekly defoliations suggests that it is not necessary to maintain a weekly defoliation strategy throughout the growing season. This idea may be explored with the concept of compensation point (CP). Plant weight decreases from
defoliation until CP and then starts to increase again. Experiments with Cirsium arvense showed that at CP between 25% and 35% of the initial root weight had been lost (Verwijst et al., 2018). In Rumex, it has been reported that the CP is reached after 25 days (Roberts & Hughes, 1939). We defoliated the plants before the CP had been reached, and thus, we are not able to determine the CP. However, our data show that when the plant’s reserves are low, it takes longer to create new leaves; this means that it would take longer before the rate of assimilation equals the rate of weight loss. In our experiments, the plants’ reserves decreased with each subsequent defoliation. This means that also the time to reach the CP increases with the number of defoliations. Thus, an optimal control strategy would combine frequent defoliations early in the season with less frequent defoliations later in the season.

The results of the farm experiment show that well-established Rumex plants, with large underground reserves, are more resilient in the face of frequent defoliation than smaller plants. When faced with a pasture in which such a well-established Rumex population is present, it seems sensible to first use grassland renewal to reduce the population (Ringselle et al., 2019). Following renewal, Rumex can be kept under control with frequent defoliation.

We conclude this discussion with a few words about the practicality and efficiency of a robot to control Rumex through frequent defoliation. Most agricultural robots proposed so far have the size and the price of a small tractor. However, defoliation of single Rumex plants may be achieved using a small, possibly solar-powered robot. Such a small robot would have a limited impact on the grass, especially when it is deployed when the grass is still short. Damage to the grass and cost of operating the robot will be limited if one considers that the robot would have to traverse the entire pasture only once a year, in order to record the locations of Rumex plants; during subsequent passes, working time and distance driven by the robot may be achieved by moving directly from weed to weed using the recorded locations.

Conclusion

Frequent defoliation is an effective method to control, but not kill, R. obtusifolius in pasture. Further research is necessary to determine the minimum effective defoliation frequency.

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Data availability statement

All data mentioned in this paper are available at https://doi.org/10.17026/dans-xpt-a2bd.

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