Ecological Studies of *Rumex crispus* L.

Propagation, Competition and Demography

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Front cover: Fruits, young rosette, and taproot of *Rumex crispus* L.
(Photo: Alexandra Pye)

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Abstract

The perennial weed species *Rumex crispus* L., or curled dock, is a major problem in agriculture in Sweden as well as in many other parts of the world. Its ability to establish quickly from seed, its persistent taproot system, high capacity of regrowth after cutting, and massive production of seed that remain viable in the seed bank for decades all contribute to the success of the weed. It is particularly problematic on dairy farms and in organic agriculture and difficult to control effectively, especially without the use of chemical herbicides.

R. crispus and other weedy dock species have been well studied since the early 1900's. However, the constant changes in agricultural practices and policies, affecting both the abundance and performance of the weed and the conditions for its control, call for a continuous renewal of the knowledge of the species.

This thesis work was based upon a set of experimental studies dealing with several different processes in the life cycle of *R. crispus*. I have investigated time and pattern of seedling emergence, the effects of competition on the performance of juvenile plants, vegetative regeneration from underground parts, and population dynamics in an agricultural field.

I found that *R. crispus* seedlings can emerge throughout the growing season and that seeds that remain on the parent plant over winter posses a certain level of dormancy, leading to later and more intermittent emergence compared to the seeds dispersed in autumn. Tillage that leads to fragmentation of the root system can stimulate sprouting of new shoots from the regenerative tissue of the taproot. Severed top fragments of roots sprouted faster and produced more shoot biomass than intact rootstocks.

Further, it was found that *R. crispus* seedlings are very sensitive to root competition in its early life stages, while it makes some morphological adaptations in response to shoot competition. To establish successfully in grassland, a large gap in the sward is required. Vegetation density during establishment of *R. crispus* plants will affect plant performance also in the long term. Low frequency cuttings had no effect on population size, but can reduce the rate of seed bank accumulation.

Keywords: curled dock, emergence, establishment, population dynamics, vegetative regeneration, ley, weed control, weed ecology

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Dedication

To my father Michael Pye - because you would have been the proudest of them all.

If you have to go, don't say goodbye
If you have to go, don't you cry
If you have to go, I will get by
Some day I'll follow you
And see you on the other side

- Smashing Pumpkins, "For Martha"

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to in the text by Roman numerals:

I Pye, A. & Andersson, L. (2008) Time of emergence of *Rumex crispus* L. as affected by dispersal time, soil cover, and mechanical disturbance. *Acta Agriculturae Scandinavica, Section B – Plant Soil Science*. In press.

II Pye, A., Hansson, M. & Torstensson, P. Effects of above- and below ground competition on morphology and growth of *Rumex crispus* L. seedlings. Submitted manuscript.

III Pye, A., Andersson, L. & Fogelfors, H. Vegetative regeneration of *Rumex crispus* L., as affected by fragmentation, burial depth, and cutting. Submitted manuscript.

IV Pye, A., Torstensson, P., Hansson, M. & Fogelfors, H. A demographic study of a *Rumex crispus* L. population in short-term ley, under varying management practices. Manuscript.

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Introduction

Weeds, by definition, are plants that grow where we do not want them to grow. They occupy space from our crops and compete with them for water and nutrients, causing yield loss. Weeds can also affect the quality of the crop negatively by taste, palatability, handling and storage properties, or even by containing substances that can damage the health of cattle or humans consuming it. Farmers have struggled with weeds in all times. Depending on climate, crops and agricultural methods, different types and life forms of weeds will dominate.

Leys for cutting, most commonly mixtures of grass and clover undersown in spring cereals, are the principal perennial crop on arable land in Scandinavia (Håkansson, 2003) and play an important role in the crop rotation especially of organic agriculture. Besides on-farm production of cattle fodder, the ley also serves as a measure for weed management, as a catch crop to prevent nitrogen loss from the field, to improve structure and organic matter content of the soil, and to avoid plant diseases in the crop rotation. Weed problems associated with ley is principally involving perennial weeds. These usually establish at the same time as the crop plants and subsequently increase their biomass in the stand with the advancing age of the ley – mainly by increasing their size but also through clonal growth and/or vegetative regeneration. This process is facilitated by the outwintering of some crop species; especially clover.

One of these perennial weeds is the curled dock, *Rumex crispus* L., which is the target species for this doctoral thesis work. In many countries in the temperate zones of the world, the curled dock is considered one of the most troublesome weeds, and among organic farmers it probably has a top position in the areas where it is abundant. In Sweden it occurs along with its relatives *R. longifolius* and *R. obtusifolius*, but due to its combination of abundance, weediness, and distribution within the area of intensively managed agricultural land, *R. crispus* is considered the most important weed species of the three. In a British survey made by Turner *et al.* (2004) over 60 percent of interviewed farmers responded that docks were their main weed management problem. Also, it is one of the most mentioned reasons why farmers are reluctant to converting from conventional to organic farming (Zaller, 2004a). In a Swedish survey focusing on farms with pastures dominated by white clover (Arnesson, 1991), docks were perceived as a problem on 45 percent of the 73 farms included. Ann-Marie Dock Gustavsson (Swedish Board of Agriculture, pers. comm.) reports that docks are without competition the principal problem at least for organic dairy farmers at the present.

The original reason why this doctoral project came to be is that there is a general agreement among farmers, extension officers, and weed scientists in Sweden that *R. crispus* has been and still is an expanding problem in Swedish agriculture. It is difficult to find official numbers to demonstrate that the frequency and size of infesting populations is actually greater today than a couple of decades ago but there is no hesitation, judging from the signals from the agricultural producers, that the perceived problem is both severe and growing (Nilsson & Hallgren, 1991; Andersson, P-A, 2007).

This thesis was based upon four sets of experiments, dealing with separate parts of the life cycle of *R. crispus*. I have studied timing of emergence from seed, effects of interspecific competition *R. crispus* seedlings, regrowth from buried whole or fragmented roots, and finally demographic changes over four years in a *R. crispus* population sown together with a ley crop. However, before proceeding to the experimental work and the results and conclusions derived from it, I will give a thorough description of the study species and also go through the factors I think may be responsible for the increase of the curled dock.

As the docks have been recognised as problem weeds for many decades, they are by now quite well-studied species. Biological studies of perennial weed species constituted an important research area before the breakthrough of chemical pesticides in the 1950's. As agricultural methods and land use have changed a lot since then, it is sometimes difficult to apply the results on today's situations and problems, even if the knowledge conveyed is very valuable. Further, the closely related dock species *R. obtusifolius* is the more important weed in *e.g.* Great Britain, and is much more studied in these areas and in total. I have tried to primarily use references to literature treating *R. crispus* specifically, but in the cases where such a reference could not be found I have instead referred to relevant studies on *R. obtusifolius* or, very occasionally, *R. longifolius*.

Background

A closer introduction to the study species

Classification, habitats and distribution

Rumex crispus L. is a tap rooted stationary perennial forb, belonging to the Polygonaceae family. In the categorisation of plant life forms made by Raunkiaer (1934), *Rumex* spp. belong to the hemicryptophytes. Characterising for this group, which includes many grasses and rosette plants, is that buds are located at the soil surface, protected by leaf and stem bases (Mauseth, 1995). *R. crispus* is considered one of the most widely distributed non-cultivated plants in the flora of the world (Hughes, 1938). As a follower of man it has spread to every continent and is known as a serious weed of agriculture in many countries (Cavers & Harper, 1964). The exact original distribution cannot now be recognised, but was undoubtedly much more restricted. The species is probably native to Europe and Africa. It does not occur in higher abundance in native plant communities, but is clearly stimulated and distributed by human activities (Zaller, 2004a).

The species occurs in a wide range of habitats, but particularly waste ground, road sides, shingle beaches, disturbed areas, temporary grasslands, and arable land. It is found on almost all soil types, except for the most acid (Cavers & Harper, 1964). In a survey of botanical compositions of grasslands in England and Wales (Hopkins *et al.* 1988), docks (including both *Rumex crispus* and *R. obtusifolius*) were most widespread in districts where there was a higher proportion of dairy farms. Fields with serious dock infestations were either mown or grazed by cattle, and particularly fields that received over 100 kg N ha-1 and which had been reseeded during the previous 8 years. This confirmed the earlier study by Hopkins *et al.* (1988) in which swards containing *Rumex* spp. were associated with mowing together with reasonably high soil fertility. The presence of docks is also associated with high inputs of nitrogen and slurry, cutting for silage and any soil cultivation activity that leads to a decrease in sward density (Courtney, 1973; Haggar, 1980). In many ways, a high incidence of docks is an indicator of defective land management (Zaller, 2004a), as over-fertilising, soil compaction, poor crop cover, and physical damage to the sward are factors that are commonly associated with *Rumex* infestation.

Life stages and development

Germination of *R. crispus* seeds is stimulated by light and fluctuating temperatures (Holm *et al.* 1977, Baskin & Baskin, 1985). Seedling emergence can occur in flushes during the whole vegetation period, depending on weather conditions (Roberts & Totterdell, 1981; Pye & Andersson, 2008). However, seedling survival among seedlings emerging earlier in the season has shown to be higher compared to later emerging seedlings in some studies (Weaver & Cavers 1979; Makuchi & Kanda, 1980). The latter concluded that one of the reasons was that establishment of seedlings was impeded by the proximity of adult individuals of the same species. Pino *et al.* (1997) on the contrary, found no or little effect of emergence time on survival.

Once the juvenile plant is established, the development goes through three phases: the rosette phase, the elongation phase, and the inflorescence phase. The typical crisped edges of the adult *R. crispus*, giving the plant its common name, first occur in the sixth leaf. The stable adult form is attained at the eighth leaf (Roberts & Hughes, 1939). Plants that germinate in the spring can develop a fleshy taproot system before autumn (Maun, 1974). Before the tap root system is established, seedlings of *R. crispus* are slow growing and poor competitors (Cavers & Harper, 1964). By the time the plant is mature, root contraction pulls the crown below the soil surface and forms a vertical underground stem (Hughes, 1938). Depending on resource availability, *R. crispus* may flower in its first year or, more commonly, remain in the rosette phase through its first winter. It produces one or usually more inflorescences that can reach up to 1 m or more. The inflorescences are branched but relatively thin. Flowering takes place in June to October; occasional single plants can flower twice in a season (Bond *et al.*, 2007). The flowers are green and mainly wind pollinated. They contain no nectar, but are occasionally visited by bumblebees collecting pollen (Cavers & Harper, 1964).

The seed is really a nut enclosed in enlarged inner perianth segments (Grime *et al.*, 1988). Part of the perianth segment can be enlarged into a corky tubercle, helping the seed to keep afloat in water (Cavers & Harper, 1964). A single plant can produce up to 40 000 seeds (Cavers & Harper, 1964); the average being about 10 000 seeds (Bond *et al.*, 2007). The seeds are highly variable in size, depending principally on the position on the mother plant but also on time of seed set and environmental conditions. The seeds can remain on the mother plant until next spring or even summer (Cavers & Harper, 1964 and personal observations, see Figure 1) and are dispersed short distances by wind or longer distances with *e.g.* animals or water. Seeds of *R. crispus* can remain viable in the soil for up to 80 years, thus a considerable seed bank can be accumulated. However, it has been estimated that the total seed loss due to death, dispersal, predation or decay can be up to 90 percent (Zaller, 2004a). I found no specific studies on seed predation in *Rumex*, but probably it is not one of the major reasons for seed loss.

There are different opinions on which proportion of plants that die after fruiting, and most likely it is dependent on the environmental conditions. Surviving plants will overwinter as a rosette and can reproduce again in one or several years. Longevity of *R. obtusifolius* has been reported up to 5 years, and probably a great deal longer (Foster, 1989). Regrowth from the rosette stage begins very early in spring with the first warm weather (Bond *et al.*, 2007), and often additional side rosettes are formed with increasing age of the plant (pers. obs. and unpublished data).

Figure 1. Detail of a *Rumex crispus* plant still carrying most of its seeds in February, 2008. Note how the most distal seeds are dispersed first. Photo: Alexandra Pye.

R. crispus has been shown to be able to produce new plants from rootstocks after only 40 days (Monaco & Cumbo, 1972). The growth of the root system is fastest in spring, and the regenerative capacity is also greatest early in the season (Kvist & Håkansson, 1985). In an adult plant, the root system of *R. crispus* can reach more than 1.5 meters down in the soil, and be almost as wide (Cavers & Harper, 1964).

Vegetative regeneration principally occurs from the fraction of the taproot consisting of underground stem tissue. The capacity of sprouting new shoots also from true root segments has been subject to contradicting opinions (Hughes, 1938; Hudson, 1955; Kvist & Håkansson, 1985) – we can agree that it is rare but still does occur under certain circumstances. Emergence (time to emergence and produced biomass) from fragmented root systems, *e.g.* by soil cultivation, is determined by fragment size and burial depth (Kvist & Håkansson, 1985; Pino *et al.*, 1995).

Significance as a weed

The main characteristics of the dock species which make them such successful weeds in agriculture are their ability to establish quickly from seed, to flower in their first year, and to produce large quantities of seeds, some of which can remain viable for very long periods in the soil (Cavers & Harper, 1964, Holm *et al.*, 1977). Seed germination can occur intermittently over several seasons, which is an important survival factor in weeds colonising agricultural land (Cavers, 1974). The plant can also withstand close grazing and mowing, and can quickly enter openings in the sward such as dung patches. The tough and fleshy storage root makes it possible for the species to persist despite injuries and disturbances by animals or management measures (Holm *et al.*, 1977).

Several studies show that *Rumex* species can cause reduced grass yields (Courtney, 1985; Oswald & Haggar, 1983). They can constitute a considerable part of the biomass (up to 70 percent in the mentioned studies) and the yield loss is proportional to the area of ground covered by dock plants. The reduction in grass growth is caused by competition from the dock plants, mainly by shading but also by below ground competition for water and nutrients (Oswald & Haggar, 1983). Courtney (1972) found that grass yields increased with up to 50 percent in fields where the dock population had been controlled.

Although *Rumex* species contribute to the total amount of herbage harvested, their presence impairs the quality of the harvest (Oswald & Haggar, 1983). As both palatability and digestibility of docks is about 80 percent that of grass, the total value of docks to grazing animals is about 65 percent that of grass (Courtney & Johnston, 1978). Both nutritive value and intake by cattle quickly decrease after flowering. The fact that docks, at least older plants, are mostly refused by grazing animals strengthens their competitive ability in pastures. The curled dock is also mildly toxic to stock (Grime *et al.*, 1988).

Population dynamics in agricultural grassland

Even though *R. crispus* to a small, but increasing, extent occurs also in annual crops such as cereals (after breaking of a ley), the main problems are associated with grasslands. In intensively managed grassland, there are three mechanisms for successful establishment of new *Rumex* individuals (Hongo, 1989):

i) Seedlings from a buried seed pool that germinate after cultivation. This is the most effective means, as a large number of seedlings can emerge and at least some of them are expected to survive.
ii) Seedlings from a buried seed pool that germinate when a gap occurs in established vegetation, as observed on locally disturbed sites such as vole- and molehills, footprints or old dung patches.
iii) Plants arising from part of the underground system split up by cultivation. This mechanism is of little importance for the total reproduction (Cavers & Harper, 1964).

Despite the very high seed production, *Rumex* species seldom establish in dense swards (Pino *et al.*, 1995). In experiments with introduction of seeds and young plants in different habitats, establishment from seeds was only possible where an open habitat existed (Cavers & Harper, 1964). Expansion of the dock population in grassland after the closing of the sward is thus mainly due to increasing size of individuals, and to clonal growth (Pino *et al.*, 1995).

The population dynamics of *Rumex* species in undamaged grassland is a typical example of the so-called 'phalanx' strategy (Klimeš *et al.*, 1993). The strategy of a phalanx species is to remain in a relatively fixed position as long as possible and to slowly colonise neighbouring areas. Their plasticity and regenerative ability is probably not critical for long-term survival since they do not have to search for patchily distributed limiting resources.

Factors possibly contributing to the increasing abundance of *R. crispus* in Swedish agricultural land

During the later half of the 20th century and up to now, far-reaching changes have taken place in the management of grasslands as well as in agriculture as a whole. Increased use of fertiliser N and chemical pesticides, increased stocking rates, the widespread switch-over from hay making to silage making, are just a few examples that can all lead to changes in sward composition and grassland flora (Hopkins, 1988). In addition, EU subsidies in combination with low prices on agricultural produce have entailed more extensive management of grassland and also a lower level of ambition. Many of these changes can be suspected of contributing, directly or indirectly, to the increasing success of *Rumex* species, including *R. crispus*. The most important are listed below.

Reduced tillage

No-till agriculture has become more common in Sweden as a consequence of high fuel prices and also as a way to reduce leakage of nitrogen and other nutrients from the soil. As an example, in the case of winter wheat planted after a winter oilseed crop, planting is to 60 percent carried out without any preceding ploughing. Lack, or reduction, of tillage will generally favour stationary perennials such as *R. crispus* (Håkansson, 2003). Mineta *et al.* (1997) found that a no-till system applied during three years increased *R. crispus* populations, and Légère *et al.* (2008) report that both diversity of weed communities and total weed biomass were greater for no-till systems than for conventional tillage systems.

Organic agriculture

The number of farms following the criteria for organic farming, which includes prohibition of the use of chemical herbicides, is steadily increasing in Sweden. In 2005, almost 20 percent of agricultural land in Sweden was under organic production, of which as much as 70 percent consisted of leys for cutting and pasture (Swedish Board of Agriculture, 2008). Of total agricultural land area, leys constituted 39 percent. The Swedish government has passed an official goal (Government Offices of Sweden, 2005) that 20 percent of all agricultural land in Sweden should be under *certified* organic production by the end of year 2010 (in 2005 it was about 7 percent). Today it looks like the goal might be difficult to reach on time, but as an incentive the subsidies for non-certified organic agriculture are being reduced.

In addition to the lacking possibility of chemical control, the crop rotations of organic farms are generally more favourable for *R. crispus* because of a greater proportion of perennial crops, such as short-term leys, compared to annual crops. Also, they more often comprise both animal and crop production, which provides several other advantages for the weed species (see following paragraphs). In organic farming forage leys are often of shorter duration (1-2 years) than in conventional farming. It can be a disadvantage for *Rumex* species if the frequently recurring disruptions caused by soil tillage for annual crops are thorough. If not, the disruptions can have the opposite effect of propagating the species.

More intensive animal production

There are several reasons to why animal husbandry can contribute to the success of *R. crispus*. Trampling damage to grass/legume swards, as well as manure droppings, provide suitable microsites for germination and establishment of *R. crispus* seedlings. The extent of trampling damage can be expected to increase if we experience continued global warming, with wetter autumns and milder winters.

The general grazing behaviour of cattle and horses include a tendency to avoid especially adult dock plants, giving the species a competitive advantage over the more palatable vegetation leading to greater seed production and nutrient reserves. As the species is also associated with over-fertilising, pastures with high stocking rates are particularly prone to severe and persistent infestations (Haggar, 1980), which is also in consistence with my personal observations.

Increasing number and size of horse farms

Horses are considered to be of increasing importance in Swedish society (Statistics Sweden, 2005), and the equestrian sector and its relevance for agricultural production is growing. Due to lack of statistics, however, the development cannot be quantified. Horses at agricultural holdings have been covered regularly, but today these constitute only one-third of all horses in Sweden. The first total count, in 2004, showed that the average number of horses per 1000 inhabitants was 31 (Statistics Sweden, 2005).

In the survey made by Haggar (1980), selective grazing by horses was stated as one of the factors likely to encourage infestations of docks. But there are also other factors that can make a horse farm a haven for dock populations. During the whole year, except for the few months when many horses are let on summer pasture, horses are often attaining their daily outdoor exercise in relatively small paddocks (in certain quarters referred to as "horse deserts") where the constant trampling, addition of manure, and complete removal of all palatable vegetation create ideal conditions for *R.*

crispus. Further, due to the greater demand for high quality horse fodder, it has become increasingly common to harvest for "hay silage", which is a product combining the properties of hay and silage. It is harvested later than traditional silage, which is mostly used for cow fodder, but instead of drying in the field it is enbaled in plastic film directly with no or very small addition of acid. The result is a product with lower water content and a higher pH value than ordinary silage, which are conditions improving the chance of survival of *R. crispus* seed through the conservation process (Humphreys *et al.*, 1997; Overud, 2002).

The increased use of slurry

The use of slurry, as opposed to the composted farmyard manure, started in the 1950's in Sweden and has increased since then. *R. crispus* seeds can pass through the digestive tracts of cattle and horses without losing their viability. Depending on the system used for manure handling, seeds can consequently be returned to the field with the manure and give rise to new individuals. The use of slurry, as opposed to composted farmyard manure, increases the survival of *R. crispus* seeds significantly (Humphreys *et al.*, 1997). However, the fact that the use of both slurry and farmyard manure is strongly associated with *Rumex* infestations (Haggar, 1980; Mikulka & Kneifelová, 1994) in leys is more probably a result of establishment of seedlings being favoured, than of seeds being spread with manure (Humphreys *et al.*, 1997).

Examples of possible non-chemical control measures

Mechanical control

Various means of soil cultivation, such as harrowing, ploughing, rotovating or other tillage methods, are among the most widely used strategies for non-chemical regulation of weeds. Mechanical control kills or damages the weeds through uprooting, burial or fragmentation. According to Nilsson & Hallgren (1991), thorough mechanical control, *e.g.* rotary cultivation followed by ploughing can have as good an effect on *R. crispus* as chemical control.

Weed harrowing early in the season is carried out to destroy emerging seedlings before, or shortly after, emergence of the crop. Careful ploughing after harvest will disaggregate and bury root parts to prevent regrowth. Other methods bring the fragmented roots to the soil surface where they can be collected or left to desiccate or freeze. However, an inadequate tillage measure that does secure either deep burial or satisfactory destruction of the regenerative parts of the root system can instead stimulate shoot production and lead to a new infestation of *R. crispus*.

Cutting

The idea of cutting of the grassland sward as a control method is that repeated removal of above-ground biomass will gradually deplete the reserves stored in the taproot of *R. crispus* so that regrowth will decrease and the new shoots will be weaker competitors for light. However, as the species possesses such a high capacity of regrowth, most studies have shown that very frequent cutting would be necessary to successfully control the population (Courtney, 1985; Niggli *et al.*, 1993; Hopkins & Johnson, 2002). Very high cutting frequency can in turn damage the crop as well, and in the long term give the weeds competitive advantages (see Dock Gustavsson, 1994, for an example with *Cirsium arvense*). Mikulka & Kneifelová (2004) concluded that a serious infestation of *R. crispus* is probably impossible to eradicate by means of cutting only.

Competition

As *R. crispus* is known to be a weak competitor in early developmental stages, a basic but important measure to prevent heavy infestation seems to be to promote a healthy and dense sward when a new ley is being established. This is important not only when *Rumex* is emerging from seed, but also when regeneration is occurring from fragments of the underground system (Zaller, 2004b). Huarte & Arnold (2003) showed that using lucerne cultivars with low levels of winter dormancy could reduce emergence of *R. crispus*, due to the competitive advantage obtained by the crop through its early establishment. In the same study, also increased sowing density had effect on the emergence of *R. crispus*. Also a number of other authors have found that a high seeding rate (Parr & Brockman, 1985; Nashiki *et al.*, 1993: Nashiki, 1995) and/or a high sward density (Hopkins *et al.* 1997) can suppress the establishment of a dock population. However, all of these reports deal with the broad-leaved dock, *R. obtusifolius*.

Selective grazing

As discussed earlier, most animals will avoid dock plants and thereby give them competitive advantages through removing the surrounding vegetation. Thus, grazing in general is not an effective control method. However, it has been reported that for instance sheep, and certain breeds in particular, actually have a preference for *Rumex* and will selectively graze both young and older individuals (Zaller, 2006). If animals with a preference for *Rumex* plants are used, the continuous removal of especially juvenile individuals would lead to a suppression of the population and especially a decreased numbers of flowering plants, leading to a smaller contribution to seed bank. In Haggars survey (1980), relatively few docks were found in fields grazed by sheep. Zaller (2006) found that sheep grazing reduced the *R. obtusifolius* population more than cutting, and that the number of fruit stands was significantly reduced in grazed plots. Mixing different types of stock can be a way of improving the effects of grazing on weed abundance. For instance Sakanoue *et al.* (1995) found that *R. obtusifolius* was better controlled when grazed simultaneously by cows and goats than by grazing of each species separately.

Biological control

Investigations of the possibilities of biological control principally deal with the Coleoptera *Gastrophysa viridula*, which feeds on *Rumex* species, and a rust fungus; *Uromyces rumicis* (Zaller, 2004a). Although both organisms can cause significant damage to dock plants, none of them have been shown to effectively eradicate dock populations. The greatest potential probably lies in the combination of biological control with other control methods.

Chemical control

To complete the picture, a few words on chemical control of dock species in conventional agriculture may be useful. In crop rotations dominated by cereals, *R. crispus* seedlings can be controlled very effectively by common cereal herbicides such as sulphonylureas and phenoxy acids. These compounds also control young plants (5-10 leaves) relatively well.

However, in crop rotations with a degree of reduced tillage and in several-year leys, *R. crispus* and other *Rumex* species have an advantage that increases the need for control measures. In some regions of Sweden, a ley component of 30-50 percent in a crop rotation is not unusual (Statistics Sweden, 2008). This has meant the introduction of a longer-lying crop in which the use of herbicides is normally very low and in which clover, which is more sensitive to herbicides than pure grass leys, is a frequent component. There are very few herbicide products available for use on leys containing clover.

Aims of the thesis

The overall aim of the thesis project was to improve the knowledge about the different stages in the life cycle of *Rumex crispus* under Swedish conditions. While the major part of the experimental work has been of a basic autecological character, the focus of the project was always on the application of the research in agricultural practise, and in particular on the development of efficient non-chemical control measures.

The main specific questions addressed by each paper were:

Paper I

- When does emergence of *R. crispus* seedlings occur in the field in Swedish populations, and how is it affected by soil cover and mechanical disturbance?
- Do seeds that remain on the mother plant over winter display a different pattern of emergence compared to those that are dispersed in autumn?

Paper II

- Is root or shoot competition most important for the early growth and development of *R. crispus* seedlings?
- Which short-term morphological adaptations can the species make in order to cope with interspecific competition?

Paper III

- What is the general capacity of vegetative regeneration in a Swedish population of *R. crispus*, measured in emergence rate as well as in biomass and seed production?
- How is vegetative regeneration affected by degree of fragmentation, burial depth, and cutting?

Paper IV

- How does mortality and reproduction change in relation to plant size and life stage, and how is it influenced by management practises?
- Which factors determine the rate of mortality and reproduction in a population of *R. crispus*?
- Can population growth and seed bank accumulation in *R. crispus* be controlled by management?

Methods

Experimental studies

The experimental work leading up to this thesis included growth chamber and greenhouse studies, where environmental conditions can be more or less controlled, as well as field experiments, to achieve a higher degree of generality and realism. Naturally, continuous observations of natural *R. crispus* populations and their life cycle have contributed to the ideas and research questions during the years that the project proceeded. I have also had input in the form of questions and comments from, and discussions with, both farmers and extension officers who have contacted me because they deal with *Rumex crispus* infestations in their daily work.

All experiments were conducted on the SLU campus, Uppsala, or within 20 km from it. Seed lots used in the experiments were also collected from Uppsala populations and, if not used immediately, stored in room temperature. An overview of the experimental work is presented in Table 1. Find below also a more specific description of the experimental design and methods used for each paper.

Paper I

Seeds from three *R. crispus* populations were harvested from the mother plants in October and sown in pots buried in an experimental field, either directly after harvest or after winter storage of the harvested parent plants at outdoor temperatures. Seeds, 100 in each pot, were sown on the soil surface or covered by a 2-cm soil layer. In addition, some of the seeds sown in autumn were also subjected to mechanical disturbance in autumn or in spring. The experiment was arranged in a systematic design with four blocks. Emerging seedlings were counted and removed between late April and mid October, after which no further emergence was observed. Time of emergence was analysed with respect to effects of population, sowing date, soil cover, and mechanical disturbance.

Table 1. *Overview of the experimental part of the thesis.*

Paper	Type of experiment	Plant material	Treatment variables	Target process
I	Pot experiment, in field conditions	Seeds, seedlings	Sowing time, soil cover, disturbance, population	Emergence
II	Box experiment, greenhouse	Seedlings/juvenile individuals	Root- and shoot competition, nitrogen level	Growth and morphology
III	Growth chamber, greenhouse	Roots	Root size, burial depth, cutting	Vegetative regeneration
IV	Field experiment	Individuals in all life stages, population	Cutting frequency, grazing	Population growth, life stage distribution

Paper II

R. crispus seeds were sown into a dense *Lolium perenne* L. sward established in boxes. Using a split-plot design, half of the *Rumex* seedlings were grown in a polythene pipe, with a diameter of 70 mm, to exclude root competition and the other half in cleared gaps of corresponding diameter. Additional treatments were fertiliser dose (high and low; equivalent to 180 and 60 kg N/ha respectively) and cutting of the surrounding grass sward to either 50 or 120 mm. After three months, all *R. crispus* plants were exhumed and washed. Dry weight for shoots and roots were measured, as well as number of leaves, total leaf area, and lamina and petiole length of the longest leaf.

Paper III

Experiment 1: *R. crispus* roots were cut into fragments (neck, tap root; upper half, tap root; lower half, and side roots). The fragments were placed in plastic dishes and assigned different test conditions for three weeks, after which sprouting shoots were counted. Experiment 2: Roots of three weight classes were selected and buried in soil in plastic boxes at 6, 12, or 18 cm depth. The experiment was checked daily for emerging shoots and the emergence date for each root was recorded. Experiment 3: Necks (top fragments) or whole roots were buried at three different depths (6, 12, or 18 cm) and after emergence (of both *R. crispus* and vegetation deriving from the natural seed bank of the soil) subjected to two cutting treatments (first harvest of all vegetation or *R. crispus* only) and a control treatment (only final harvest). The experiment was terminated after 149 days, and shoot dry weight and seed dry weight of *R. crispus* plants in each box were measured

Paper IV

R. crispus was sown together with a mixed grass/legume ley in a 0.7 ha field. In 24 permanent 1.5 m^2 plots, all emerged *R. crispus* seedlings that were found (initially 778 individuals in total) were tagged and registered. In year 2 and 3, two cutting treatments (one or two harvests) were applied, and half of the field (12 plots) was also grazed by sheep during six weeks after the second harvest. During a period of four years, the plots were revisited twice each growing season and all individuals were checked for survival and life stage (seedling, juvenile rosette, adult rosette, or reproductive adult). Once a year number of rosettes, leaves, and reproductive shoots were counted, and measurements were made of lamina and petiole length of the longest leaf and of flower/fruit stand size.

Statistical analyses

The main tool for statistical analysis of the experimental data has been general linear or mixed ANOVA procedures. Fisher's or Tukey's post-hoc tests have been carried out to investigate differences between groups. In paper III, a method of survival analysis was also performed on emergence data. For paper IV, we used transition matrix models to analyse the transitions between life stages in the weed population, chi-square tests to compare life stage distributions between years and treatments, and logistic regressions to investigate relations between plant traits and treatment factors.

Results and discussion

Paper I - Germination and emergence

Most literature sources state that germination and emergence of *Rumex crispus* in the field occurs mainly in two flushes – early spring and in autumn. The lack of germination during summer is suggested to be caused by the seeds entering secondary dormancy. Personal observations, however, indicated that emergence of seedlings under Swedish conditions (*e.g.* cold springs and dry conditions in early summer) is more intermittent and takes place throughout the vegetation period. Also, as seeds are dispersed from the mother plants all year round, although most of them in late autumn, winter and early spring, we were interested in the possible difference in germinability and dormancy between seeds that are dispersed before winter and seeds that remain on the mother plant until the following spring.

Our emergence study showed the great variation between different populations that is typical for the species. It also confirmed that emergence can continue throughout the whole growing season, but the timing was strongly dependent on dispersal time. Emergence from seeds sown in autumn showed a distinct peak in the first half of May, while peak emergence for seeds sown in early spring did not occur until late June (Figure 2). Autumn sowing also led to more concentrated emergence, while seedlings from spring-sown seeds showed a more intermittent emergence pattern. After September, almost no further emergence took place. The light requirement of the species for germination was indicated by a higher rate of emergence from seeds sown on the soil surface than from covered seeds. Stirring after sowing had a positive effect on emergence compared with emergence from undisturbed, covered seeds.

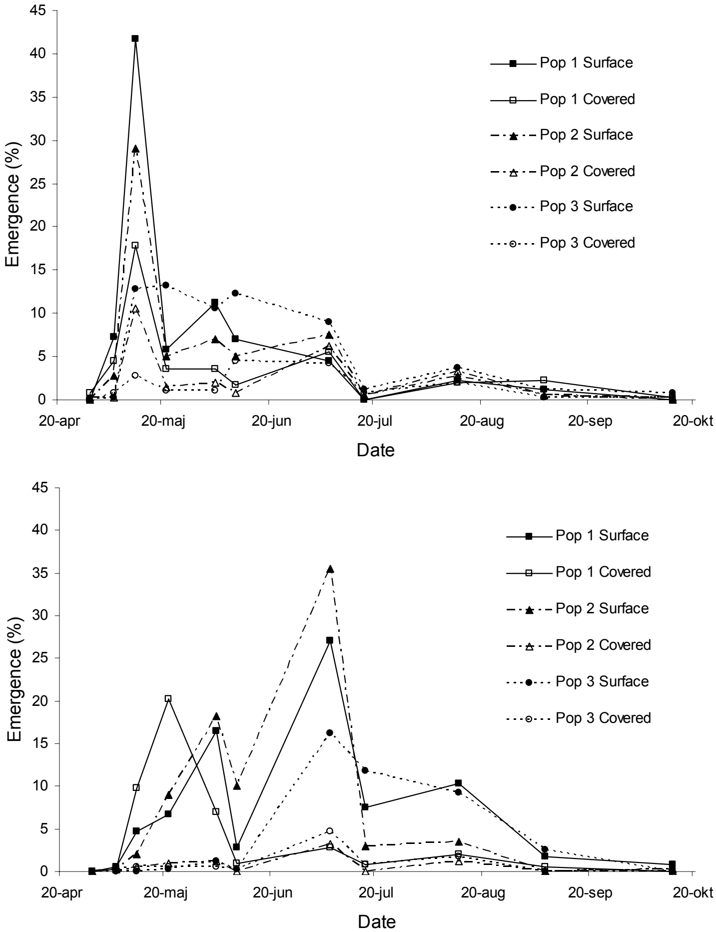

Figure 2. Effects of population and soil cover (seeds sown on soil surface or covered with 2 cm of soil) on emergence over time for seeds sown in October 2003 (top) and seeds sown in April 2004 after dry winter storage on the parent plants (bottom).

From these results one can draw the conclusions that seeds that remain on the mother plants over winter and are dispersed in spring possess a certain level of dormancy, which is gradually broken during spring and early summer. The difference in dormancy can be due to lack of cold stratification in the seeds remaining on the plants, as these seeds are not imbibed before winter (Baskin & Baskin, 1978). When dormancy is broken, lack of germination and emergence during summer is probably due to lack of soil moisture or a consequence of a vegetation canopy inhibiting germination of the *R. crispus* seeds. Seed germination that occurs intermittently, and also over several seasons, is an important survival factor in weeds colonising agricultural land (Cavers, 1974). It is also of great relevance for farmers to be able to predict the time and distribution of emergence when planning for control measures.

Paper II - Interspecific competition

The exclusion of root competition from the grass sward was the strongly dominating factor influencing the performance of the *Rumex* seedlings. Seedlings protected from below ground competition through root barriers were, on average, 200 times larger than plants without root barriers (Figure 2). The former also had more leaves and a greater total leaf area, and higher whole-plant dry weight (see photo). Fertiliser dose had effect on seedling size only in the group without barriers. In seedlings protected from root competition, nitrogen was obviously not limiting.

Shoot competition strongly affected plant morphology, causing thinner and fewer leafs with longer petioles where the surrounding grass sward was higher. This is an adaptation that will bring the leaves higher in the canopy to compete more efficiently for light, and it was more explicit when nutrient availability was higher. Apparently, long petioles in relation to lamina are important investments when light is scarce.

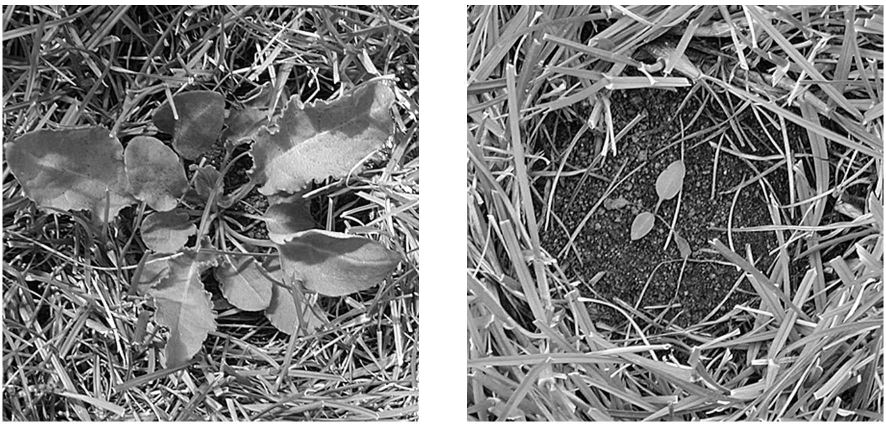

Figure 3. Juvenile plants of *Rumex crispus* growing with (left) and without (right) root barriers in a dense sward of *Lolium perenne*. Photo: Alexandra Pye.

Leaf size rather than number of leaves was affected when plant growth was limited by competition. The same pattern was found in other *Rumex* species, by Haugland (1993) for *R. longifolius* and by Jeangros & Nösberger

(1990) for *R. obtusifolius*. Total leaf area decreased with stronger competition, but the specific leaf area (SLA, leaf area per unit shoot weight) simultaneously increased so that the loss was partly compensated for.
Although root competition resulted in almost zero growth and very small plant size, mortality among these seedlings was very low throughout the duration of the experiment. This shows that the species is capable to survive in a stunted state for a prolonged period of time.

The main conclusion is early growth of *R. crispus* is very sensitive to particularly below ground competition. The plants can make morphological adaptations in response to shoot competition, if nutrient resources are available. In order for *R. crispus* to establish and grow in a grass sward, a large gap in the vegetation is required.

Paper III - Vegetative regeneration

Sprouting occurred mainly from the neck of the roots, consisting of underground stem tissue. Some shoots were observed also from the upper half of the true taproot and from a side root. We cannot be entirely sure that no stem tissue was accidently included also in these parts, neither can we exclude the possibility that regeneration can actually occur from true root fragments under certain circumstances. No difference in sprouting was found between different test conditions.

Emergence from buried whole roots was positively related to root size and negatively related to burial depth. Time to first emergence was defined by an interaction between the two factors, indicating that deep burial can enhance the effect of fragmentation. Roots larger than 100 g gave rise to a high degree of emergence from all burial depths, while emergence from roots weighing 20-30 g was less than 30 percent from 12 cm and nonexistent from 18 cm. This implies that it is extra important to bury roots on adequate depth (about ploughing depth) if the *R. crispus* population consists of adult plants.

When emergence and shoot production were tested under different cutting treatments, the severed top fragments of the roots sprouted faster and produced more shoot biomass than intact rootstocks, even at a second harvest (Figure 4). We hypothesise that this is due to a triggering of shoot initiation by fragmentation. As the boxes were well fertilised and watered, stored resources showed to be less important than fast emergence, which led to a competitive advantage and a quick start to utilise light and soil resources.

R. crispus shoot biomass at final harvest was reduced in the treatment where all the vegetation in the boxes was cut, compared to the control treatment. The selective harvest, where the *Rumex* individuals were picked out of the boxes as if they were selectively grazed, led to a strongly inhibited shoot production with low or zero seed production. Both shoot biomass and seed production were affected by the type of root fragment used and by an interaction between burial depth and competition treatment.

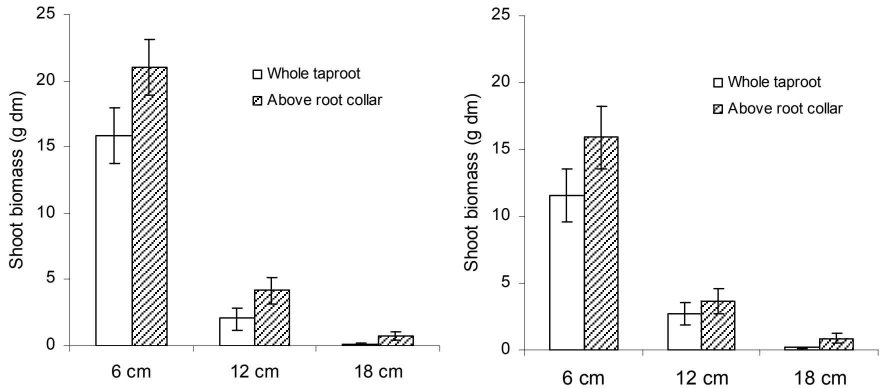

Figure 4. Regeneration from roots of *R. crispus*. Dry matter biomass (mean ± SE mean) at a first cutting (left) and second cutting (right) for different burial depths (6, 12, or 18 cm) and underground fragments (whole root or the severed neck only).

The results from these experiments have clear implications for soil tillage as a weed control measure against *R. crispus*. If tillage is carried out as weed control it is important that root fragments are buried at ploughing depth, especially if the weed population consists of adult plants. The necks of the roots have a very high regenerative capacity and must be paid extra attention. If it is not infallible that the necks will desiccate or freeze completely if they are left on the soil surface after cultivation, they must be buried deeply - preferably deeper than 18 cm.

Paper IV - Population dynamics

Total mortality during the four year period of the field experiment was 24 percent, and total proportion of plants reaching a reproductive stage (*i.e.* flowered at least once) was 23 percent. Plant size followed a normal size distribution after logarithmic transformation. The life stage distribution for all years, as compared between the two field sections included, is presented in Figure 5.

The probabilities of both reproduction and mortality were principally dependent on rosette size in the previous year. Mortality was negatively related to plant size in all years and areas. Very few plants died after flowering and seeding. Instead, mortality was highest among the smallest and thus most vulnerable individuals.

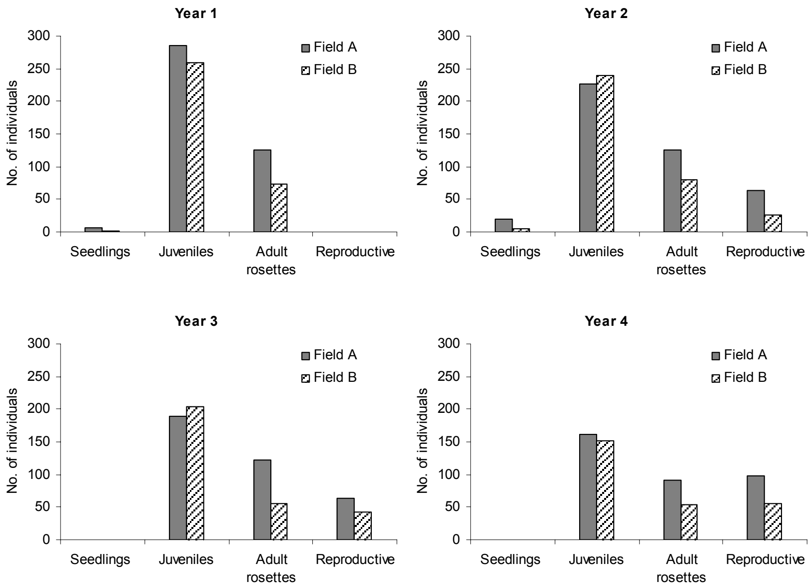

Figure 5. Distribution of life stages (number of individuals) of *Rumex crispus* in two field sections (A and B), for all four years of the population study.

Recruitment of new seedlings to the population was very low during the experimental period. This is in consistence with results of for instance Cavers & Harper (1964). Germination of *R. crispus* seeds is inhibited under a leaf canopy (Baskin & Baskin, 1998) and establishment and survival of *R. crispus* seedlings are reduced in the proximity of adult individuals of the same species (Makuchi & Kanda, 1980). However, we calculated that even a very low recruitment frequency can have an important impact on population growth.

There was a clear effect of initial sward density on the performance of the *R. crispus* population, which reflects the sensitivity of the species to competition in early life stages. In plots where the ley sward was poorly established in the first year, *R. crispus* plants were significantly larger, which in turn resulted in lower mortality, better chances of reproduction, and higher reproductive output. This effect remained through the experimental period.

Due to practical limitations, we could not statistically test the effect of sheep grazing in this study. We did not observe any obvious effects on the *R. crispus* population such as the reduction in reproductive output that Zaller (2006) reported as a result of sheep grazing. The variation in life stage distribution between the two fields was instead due to differences in plant size that appeared already in the first year, *i.e.* before the different treatments were applied.

Using the results of our transition matrices and data from 8 studies of seed viability over time, we designed a model to simulate the accumulation of the *R. crispus* seed bank under varying conditions. We found that within a few years within the establishment of a *R. crispus* population in a field, the density of seeds in the seed bank can build up very rapidly. Cutting and removal of the reproductive shoots from the field before seed setting can reduce the contribution to the seed bank. In this aspect, and considering the fact that *R. crispus* generally does not produce seeds in its first year, shorter duration of leys in the crop rotation is favourable for the control of *R. crispus*, as the accumulation of the seed bank will not be as fast in the first two years.

Synthesis and conclusions

Thoughts on the relevance of the *Rumex crispus* problem

The gathered opinion seems to be that the curled dock is undergoing an increase in Swedish agricultural land, although we lack proper surveys to confirm this increase in numbers. Regardless of this, however, the curled dock is a highly potent weed species that we need to keep constant focus on. Its remarkable capacity of rapidly expanding infestation if conditions are favourable makes it somewhat of a ticking bomb in the agricultural weed flora.

The contemporary success of the species in agricultural systems can be summarised as the result of the simultaneous intensification and "extensification" of agriculture. While farms and holdings are growing, farm animal stocks are increasing with more animals per hectare, and inputs of fertilisers are very high, number of labour hours per hectare is at the same time steadily decreasing. Due to the scale of the production, management is highly mechanised and most weed control measures are carried out on field level.

Hand pulling and digging are probably still among the most cost-effective control measures against established plants, but few farmers today will adopt these methods which are both time-consuming and physically demanding. However, many of the other available non-chemical control methods used against docks are successful only in the short term. Perhaps there is a need for a more holistic approach to this particular weed problem and its solutions, both on a scientific level and on a farm level.

Main findings of the experimental work

- Emergence occurred throughout the growing season, indicating the absence of secondary dormancy in the summer. Mechanical disturbance of the top soil layer favoured emergence in the seeds that were consequently brought to the surface. Seeds remaining on the mother plant over winter showed a later and more intermittent emergence pattern than seeds that were dispersed in autumn. Dispersal time affected timing of emergence but not the total emergence rate.

- Root competition strongly reduced growth in *R. crispus* seedlings, while it made morphological adaptations in response to shoot competition. As seedlings are sensitive to especially root competition in the early development stages they require a large gap in the vegetation to establish successfully. Seedlings can remain in a prolonged juvenile state if competition or other unfavourable conditions inhibit growth during a period of time.

- Fragmentation of the root system can stimulate the sprouting of new shoots from the regenerative tissue of the taproot. Severed top fragment ("necks") of the roots sprouted faster and produced more shoot biomass than intact rootstocks, even at a second harvest – despite the obviously smaller energy reserves. The probability of emergence of regenerative shoots from buried rootstocks is depending on root weight (positive relation) and burial depth (negative relation).

- The competitive situation in field during the establishment phase of new *R. crispus* individuals will increase mortality and reduce plant size. This effect is not only found in the year of establishment but will influence the performance of the population for several years. Low frequency cuttings do not have any major effect on plant size or life stage distribution, but can reduce the contribution to the seed bank.

Implications for weed control

As all the collected experience from farmers, extension officers, and scientists tell that an established dock population is very difficult to eradicate at a reasonable cost and effort, it seems hindering docks seeds to germinate at the sowing of a new crop is most important. If problems already exist, the most effective measure is probably thorough cultivation followed by an extended period of bare fallow during which any emerging seedlings or regenerating plants can be destroyed.

If a field containing *R. crispus* plants is tilled for weed control, it is crucial that root fragments are buried on ploughing depth, especially if the weed population consists of adult individuals. Alternatively, they could be left on the soil surface for complete freezing or desiccation. If the field must be reseeded shortly, it is important to use a fast-growing and suppressive crop. The importance of a healthy, dense crop sward without gaps can not be overrated when it comes to preventing *R. crispus* infestation. Injuries to the vegetation through wheel tracks, trampling by cattle, or just poor establishment of the crop, will provide the microsites necessary for *R. crispus* to establish if there are seeds present.

In summary, my conclusion is that there is not any single remedy for control of the curled dock. Instead, integration of different control measures adapted to each farm and situation is demanded for. Each farmer must consider his or hers specific system in terms of soil type, crop rotation, fertilising, animal husbandry, labour resources etcetera and, hopefully with the competent help of advisers, work out a suitable set of methods.

Questions for future research

A closer investigation of the grazing behaviour of different animals and the effect on the abundance, propagation and life stage distribution of *R. crispus* would be very useful. It may be, for instance, that combining more than one type of animal would enhance the suppressing effect on the weed species, and at the same time reduce trampling damage during wetter periods.

As almost no non-chemical control measures have showed competent to efficiently eradicate *R. crispus* populations, it seems that the most important challenge is to stop the seeds from germinating at the sowing of the ley. If we can find a method that is successful in this matter, there is no need for absolute zero tolerance against single plants in the field.

Besides the factors contributing to the success and/or increase of the curled dock in Sweden discussed in the background section of this thesis, it is also of uttermost relevance to think about how this species will be affected by future climate change. Dock species have been subject to some studies regarding primarily elevated CO_2 concentrations, but we do not know enough to predict how their distribution and performance could change as a consequence of raising temperatures (in particular milder winters), intensified solar radiation, and increased atmospheric CO_2 in combination.

In year 2009, a field trial will be initiated on the same field on Årby Farm that was used for the population study in this thesis. In the light of the knowledge derived both from the experimental work and from the literature study, different management measures to eradicate the established population will be evaluated.

As we concluded that even a very low frequency of new recruitment of *R. crispus* in established leys and pastures can have a great impact on population growth, it would be of great interest with additional field studies on germination, seedling recruitment and survival in these habitats.

Finally, I think that a well-planned interview study with farmers would be an invaluable contribution to the work of trying to pin-point which factors and management measures really are significant for the abundance of *Rumex crispus*, and which are not.

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