



## Review Article

# The potential for the biological control of *Rumex obtusifolius* and *Rumex crispus* using insects in organic farming, with particular reference to Switzerland

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### Abstract

*Rumex obtusifolius* and *Rumex crispus* are pernicious weeds throughout their native and introduced ranges. Infestation of grassland by *R. obtusifolius* is consistently cited by organic farmers as a particular cause for concern, although both species prove difficult to control even when chemical interventions are allowed. Established plants of both species possess a large and persistent taproot that contains a large reserve of resources. This allows individual plants to tolerate repeated defoliation. The history and growing importance of organic agriculture in Switzerland is outlined. Control methods compatible with organic agriculture are reviewed, including various weeding, mowing and cultivation strategies. The potential for limiting *Rumex* populations through sward management is discussed in relation to competition studies. Methods for depleting the seed bank and limiting seed production are also discussed. Classical and neo-classical, inundative and augmentative approaches to *Rumex* biological control are considered. Potential insect control agents, both native and non-native, are evaluated on the basis of studies carried out in Europe and elsewhere, and from the results of an Australian classical biological control programme. It is concluded that the augmentation of native natural enemies is the best approach for *Rumex* control for organic agriculture in Switzerland, although if the classical approach gains more acceptance in Europe, then non-native agents should also be considered for use in a neo-classical approach.

### Keywords

*Rumex*  
dock  
biocontrol  
biological control  
weed management

## 1. Biology and Distribution of *Rumex*

There are 19 species of *Rumex* in Switzerland according to the Swiss Flora [1]. However, it is two of the larger species, *Rumex crispus* L. and *Rumex obtusifolius* L. (Polygonaceae), that are the most troublesome weeds [2,3]. Historically, *R. obtusifolius* has been particularly associated with disturbed ground, short-term leys and badly managed grassland but is now a widespread problem across many farms [4,5]. On organic farms in Europe, the weed is consistently identified as a major problem, with farmers having a very low tolerance for its presence in both the UK (G. Davies, personal communication) and Switzerland (A. Luscher, personal communication). Its adaptation to growth on naturally disturbed environments, such as river banks and dunes, makes it ideally suited to colonizing gaps and wasteland produced by human activity [6].

If enough water is available, *R. obtusifolius* appears to have few climatic limits on its distribution, occurring naturally from north of the Arctic Circle in Norway southwards through the rest of Europe, with the exception of the Mediterranean [6]. The plant has also been introduced to, and is now widely established in, South America, Australia and Japan, and is a weed throughout its range [7]. In addition to this wide climatic tolerance, Cavers & Harper [6] showed that the plant is capable of growing from seed on a wide range of soils, with only the most acid soils, such as those from peat bogs, inhibiting growth [6].

*Rumex obtusifolius* plants usually consist of a basal rosette of leaves and a large, fleshy taproot. The leaves develop individually as tightly rolled leaf spikes. These spikes unfurl about a week after initiation, the leaves going on to expand to a maximum size of 40 cm long by 20 cm wide (I. P. Keary, per-

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sonal observation). Leaf area and stem length are very plastic in response to environmental cues, especially light [8]. Developmental rates and overall plant size also vary a great deal between individuals grown in similar conditions (I. P. Keary, personal observation). During flowering, a tall spike up to 150 cm in height is produced which bears the inflorescence. Following flowering, the plant undergoes defoliation. This can result in a complete loss of leaves for up to two months [9]. The number of seeds produced is highly variable, from about a hundred to a maximum of 60,000 [6] or 80,000 [10]. The seeds are small and highly dispersive. They are capable of being moved long distances by wind and animals [6], and can be transported both on the coats of livestock and via their dung [11]. However, the majority of the seeds tend to be found clumped close to the parent plant [3]. Flowering seldom takes place in the first year of growth (although it has been recorded as early as 9 weeks after germination [3]), thereafter the plant normally flowers once a year, but twice is not uncommon [6].

The seedlings appear throughout the year, although typically there are two large flushes in March/April and September/October [6]. Several attempts have been made to quantify seedling survival after germination, Cavers & Harper [12] and Makucki & Kanda [13] finding that in a closed sward, seed germinated but did not survive. Gap colonization is therefore an important means of establishment for the weed and the size of the gap is important to both germination and survival; proportionally more seedlings emerged in small gaps, but more survived in larger gaps [10]. Hongo [14] found higher levels of survival in newly sown grassland, although he gives no indication of how advanced the grass sward was when *R. obtusifolius* seed was sown. Seedlings that emerged the following year suffered high mortality, suggesting that in year 1 the sward was not fully established and so was less competitive. Jeangros & Nösberger [8] demonstrated that root competition was the most important aspect of the *Rumex*-grass interaction in terms of the seedlings; shading had little effect on growth as an increase in specific leaf area acted to reduce its effects.

The plant is a hemicryptophyte, dying back in autumn so that only a few small leaves remain. During winter, the majority of the plant's mobile resources are underground in the root system and protected from freezing damage until the following spring, when the foliage rapidly regrows [6]. Once the taproot is established, the plant becomes very difficult to remove. It is able to tolerate frequent defoliation, drawing on its reserves to replace the lost foliage [8].

If the taproot is split during cultivation, the fragments can regenerate to produce new plants [15]. Work by Pino *et al.* [16] has shown that only the underground stem above the root collar can produce such regrowth. Despite this finding, it is still common practice to remove at least the upper 9 cm of the root system to prevent regrowth [17]. The under-

ground stem system can also split naturally with age and secondary root systems develop, allowing the plant to spread clonally in closed habitats [16].

## 2. Status of *Rumex* as a Weed

Both *R. crispus* and *R. obtusifolius* are typically weeds of agricultural land, although *R. crispus* tends to be more associated with arable land while *R. obtusifolius* is more normally found in grazing land, particularly heavily managed pasture [3]. As a weed of pastures and meadows, *R. obtusifolius*' main effect is to reduce the value of infested land as grazing for livestock. Courtney & Johnson [18] found *R. obtusifolius* to be only 65% as valuable as grass as grazing material because of a combination of reduced palatability (and therefore grazing levels) and reduced digestibility.

Mature *R. obtusifolius* plants also suppress the grass yield of pasture. Oswald & Haggart [19] found that increasing ground cover by *Rumex* reduced grass yields, as did increasing *Rumex* density. According to Courtney [20], this effect is greater when the pasture is cut 3–4 times a year (a 70% reduction in grass yield) rather than 5–7 times a year (a 16% reduction).

These problems are exacerbated by *R. obtusifolius*' ability to exploit nitrogen efficiently. Niggli *et al.* [21] found that increases in fertilizer had no negative effect on the weed. Jeangros & Nösberger [8] found that higher levels of nitrogen fertilization were of net benefit to *R. obtusifolius* seedling growth, particularly when shoot competition with the sward was reduced.

As already noted, *R. obtusifolius* cannot establish itself from seed against an established sward of vegetation [12,22]. However, the seeds can remain viable in the soil for many years. A very small number of seeds retain viability after 80 years burial [23] and around a third remain viable after 20 years [24]. This allows the seeds to take advantage of any gaps that appear [25], even if the parent population has long disappeared. The persistence of its seeds, combined with the longevity and seed-producing capacity of the mature plants, means that *R. obtusifolius* is able to make a large contribution to the soil-borne seed bank of any areas it infests: Hunt & Harkness [26] found  $5 \times 10^6$  seeds per acre ( $1.24 \times 10^7$  seeds per ha) in the top 15 cm of soil. This extends the problems presented by the weed beyond the life span of the current mature plants until the seed bank is exhausted. The length of this period can be influenced by a number of factors including depth of burial of the seed and rate and type of disturbance, which in turn influence germination rate [22,27].

The system of clonal spread, described above, also allows *R. obtusifolius* to spread in a closed population and it has been suggested that this system allows the weed to increase the space it occupies [16] and, thus, its contribution to the sward.

### 3. Suggested Control Methods

A number of control methods have been suggested to suppress/reduce *R. obtusifolius* incidence in pasture. The importance of reduced seed input was highlighted by Brenchley [28] who stressed the need for proper composting of manure to eliminate seeds that survive passage through grazing animals' digestive tracts and are consequently spread with slurry and manure [3,29]. Seed viability can be eliminated by composting and slurry fermentation, provided that the appropriate conditions are maintained. For example, germination of *R. obtusifolius* seeds from aerated slurry is much reduced and is eliminated in slurry fermented for methane production for 4 weeks or more [30].

Hand weeding was also advocated by Besson *et al.* [30] to remove established plants and is still suggested for use in small areas, or where labour costs are not prohibitive [31]. However, using this method on larger areas incurs a severe time penalty: Tsaschli & Dubois [32] found that controlling *R. obtusifolius* infestation manually took an extra 48 h labour per hectare per year. Cavers & Harper [6] suggested a series of carefully timed rotary cultivations for the control of seedlings, although they noted that this method has limited use against mature plants because of the ready regrowth from root fragments. Some authors [26,33] suggest that the problem of regrowth can be reduced by leaving the ground as a bare fallow following a rotary cultivation in spring, so that the unearthed root fragments are killed by desiccation. The work of Pino *et al.* [16] on regeneration of plants from root fragments suggested that such cultivation-based approaches, with modification, may have some merit: a shallow cultivation to sever the underground shoots below the root collar followed by a deeper cultivation to submerge the bud-bearing shoots to a depth at which regrowth is prevented could give good control, although this method has not yet been tested in the field. However, any cultivation-based approaches are compromised by the fact that the disturbance of the soil is likely to promote high levels of germination from the seed bank.

Chancellor [34] focused on the depletion of the weed seed bank through allowing germination before destroying the seedlings. Such seed bank depletion would be accelerated if germination could be enhanced to include dormant seeds, perhaps by the application of naturally occurring chemicals [35].

Invasion by seed could be reduced if the seed set and/or seed viability were to be reduced by some means. Maun & Cavers [36] found that the average seed weight could be reduced in *R. crispus* by the removal of the cauline leaves prior to flowering. However, these lighter seeds were no less viable than larger seeds from control plants. Bentley *et al.* [37] went on to show that in *R. obtusifolius*, seed number and weight were significantly depressed by grazing by *Gastrophysa viridula* (De Geer) (Col., Chrysomelidae), although germination levels were again unaffected. Time taken to germinate was increased

for small *R. obtusifolius* seeds [38], but no differences in plant size were detectable 4 months after germination (although differences were present after one month). This study did not examine how seeds of different sizes fared under interspecific competition from a grass sward, but the authors suggested that plants from larger seeds would be at an advantage [38,39]. Even if such effects do occur, this does not guarantee establishment will not occur – the smaller seeds will still be able to take advantage of any suitable gaps appearing in the sward. Rather, it is likely that probability of establishment will be less as the seedlings will need longer to reach a stage at which they can compete with the sward.

Courtney [20] examined whether or not manipulation of the sward could be used to suppress *R. obtusifolius*, and found that frequent cuts and high nitrogen fertilization reduced the contribution of the weed to the sward. Jeangros & Nösberger [8] studied the effects of two nitrogen fertilizer regimes on competition between *R. obtusifolius* seedlings and a *Lolium perenne* L. (Graminae) sward. They found that although increasing nitrogen fertilization from 40 kg/ha to 80 kg/ha increased sward growth, and thus shading of the *R. obtusifolius* seedlings, there was no difference in the size of *R. obtusifolius* plants grown under shoot competition and full (shoot and root) competition with either nitrogen regime. However, *R. obtusifolius* size increased with raised nitrogen levels under no competition and root competition. Therefore, increased nitrogen fertilization offers little advantage in terms of reducing *R. obtusifolius* growth: suppressed plants remain suppressed, but those plants that are able to escape competition to some degree do just as well or better under higher nitrogen levels. Niggli *et al.* [21] also studied the effects of nitrogen fertilization, this time on older plants (6–8 leaves) and in combination with different grass species and cutting regimes. *Rumex obtusifolius* was strongly favoured by increased nitrogen levels and decreased cutting frequency against all species of grass used. These results lead to the conclusion that *R. obtusifolius* cannot be controlled by grass competition, variation in cutting frequency or nitrogen fertilization. Increased cutting frequencies may offer limited control, but would be likely to increase disturbance and thus opportunity for new seedlings to establish, while increasing nitrogen to combat this by increasing sward growth would also benefit established *R. obtusifolius* and seedlings growing in any gaps. Hopkins & Johnson [40] came to a similar conclusion; none of their treatments (cutting height, cutting frequency and nitrogen fertilization) could offer complete control of an emerging *R. obtusifolius* infestation. However, they suggested that the treatment components could be incorporated into management guidelines to aid in the control of the weed.

### 4. Organic Farming in Switzerland

Organic farming has expanded rapidly in Switzerland, the number of organic farms increasing from

803 in 1990 to 5400 in 2000 [41]. This increase is projected to continue as consumers continue to demand organic produce. In Switzerland, organic farms must meet requirements beyond those of the European Union (EEC Regulation 2092/91). For example, Swiss regulations demand that 7% of land on an organic farm must be given over to ecological compensation areas (ECAs), and if the private Bio Suisse standard is to be achieved at least 5% of a farm's permanent grassland must be extensively managed [41].

Swiss farms are typically small, the average size in 1998 being 14.2 ha, and are fulltime holdings [41]. In addition, the amount of time farmers are prepared to put into management is often very high, some farmers devoting over 1000 man-hours/year to *Rumex* control alone (F. Strasser, personal communication). However, this level of management is not feasible for all farms and is only possible at certain times of the year when the labour is not needed for other tasks. Therefore, any reduction in the effort necessary to control persistent perennial weeds such as *R. obtusifolius* would be an important advance.

## 5. Strategies Available for Use in a Control Programme

### 5.1. Formation of New Pest–Control Agent Associations: the Neo-Classical Approach

Classical biological control (the control of an exotic pest in its introduced environment through the establishment of a control species that shares the pest's native range) [42] is implemented through small-scale inoculative releases of the control agent across a target area, with the aim of producing a self-sustaining population. However, as *R. obtusifolius* is native to Switzerland the classical approach is not appropriate. The modification of the classical approach that has been suggested for the control of native weeds is to introduce exotic control agents that are found on close relatives of the weed growing in similar climatic areas elsewhere. Hokkanen [43] suggests that the 'neo-classical' method, as the formation of new associations has also been called, should be the preferred approach for selecting agents.

In neo-classical biological control, the likelihood of the successful establishment of the control agent (and subsequent control of the target pest) is increased by the probable lower level of predation and parasitism of the agent in its new environment. In addition, and here the neo-classical biological control agent differs from a classical agent, the probability of there being coevolved host resistance to feeding damage on the 'new' host plant is reduced, and this is likely to further increase the effectiveness of the newly introduced herbivore [44,45]. The principles behind the neo-classical approach are considered to have potential for controlling native pests [46–48]. The procedures for selecting potential neo-classical control agents are similar to those employed in classical biological control (see Forno & Hartley [49] for a summary).

### 5.2. Non-Classical Control Methods

The inundative approach consists of the periodic release of massive numbers of control agents (typically native species) across a target weed population to control it by inflicting high levels of damage. Initial development and subsequent production costs can be high, particularly when insects are being used, because of the large numbers of agents per release and, in many cases, the repeat applications needed. However, the method has the advantage of achieving control in a relatively short time (if successful) and it can be used for native agents so that pre-release host-range testing may be deemed unnecessary. There are few examples of inundative control using insects; high production costs make it more suited to pathogens [49]. Julien & Griffiths [50] list some programmes that have successfully utilized native species for the biological control of weeds, several with some success. For instance in the former Soviet Union, the pupae of an agromyzid fly, *Phytomyza orobanchia* Kaltentbach, were collected and stored during winter. The fly, which was released wide-scale prior to the emergence of new shoots in spring, achieved good control of broomrape (*Orobanche cumana* Wallr. and *Orobanche ramosa* L. [Orobanchaceae]). A similar strategy used the moth *Bactra verutana* Zeller (Lep., Tortricidae) against *Cyperus* spp. By releasing *B. verutana* early in the season, when natural population levels were low [51], control of the weed was improved.

Release programmes can also attempt to redistribute agents within a country to areas where they did not previously exist. Although this circumvents the regulatory hurdles associated with introducing an agent across national borders, the same underlying concerns may remain valid. However this approach has been used successfully. In Australia approximately 800 ha of the weed *Cassinia arcuata* R.Br. (Asteraceae) was reported to have been killed within 2 years through the redistribution of *Austrotachardia* sp. bugs and pastures were regenerating in these areas [52,53]. In Thailand, releases of the noctuid *Spodoptera pectinicornis* Hampson against the ubiquitous water lettuce, *Pistia stratiotes* L. (Araceae), have resulted in the moth becoming widespread across the country, giving excellent control and replacing the use of herbicides [50]. However, there have also been failures where the released herbivores have failed to become established (e.g. redistribution of various native chrysomelid beetles has failed to control *Convolvulus* spp. in Canada [54]).

An alternative strategy, the augmentative approach, has been redefined with respect to pathogens and weeds by Müller-Schärer & Frantzen [55] as the 'system management approach'. This approach is based on the management of the weed–pathogen system to maximize the spread and severity of the disease, using the pathogen as a stressor of the weed, in concert with other measures designed to limit the weed's impact rather than eradicate it.

The same principles are applicable to strategies utilizing insect control agents essentially involving the identification and manipulation of factors that limit or enhance the abundance and effectiveness of the control agents [56]. Several possible measures to increase the abundance of indigenous herbivores have been discussed by Bacher [57]. The manipulation of key factors that affect population density (birth and death rates, immigration and emigration) can increase the abundance of a natural enemy and thus may lead to higher levels of control. Until now, the augmentative approach including habitat and management modifications to encourage beneficial herbivores has remained largely a theoretical concept, and therefore only a few practical examples have been described. Amelioration of food quality and/or quantity can lead to increased fecundity and fertility of the herbivorous insect, hence an increased birth rate (see Awmack & Leather [58] for a review). However, measures of fitness can be differentially related to host plant chemistry [59]. Improvement in food can be achieved by such measures as the propagation of alternative host plants, the maintenance of food resources throughout the growing season in a crop situation or the application of fertilizer to the weed. For example, Hatcher *et al.* [60] found that the *Rumex* herbivore *Gastrophysa viridula* responded differently to nitrogen fertilization depending on its form (nitrate or ammonium) and the amount applied. Obviously, the effects of any measures should be of greater benefit to the control agent population than to the plant, thus leading to an overall reduction of weed biomass. This was well illustrated in the control programme against the floating fern *Salvinia molesta* Mitchell (Salviniaceae) in Australia: plant nutrient status was critical in successful control by the weevil *Cyrtobagous salviniae* Calder & Sands (Col., Curculionidae) [61]. In highly disturbed agricultural land, provision of refugia may be advantageous, favouring natural immigration and reducing emigration through the provision of suitable mating, aestivation and hibernation sites.

According to Valenti *et al.* [62] there is theoretical and empirical evidence to suggest that native herbivorous insects have the potential to be manipulated successfully as biological control agents of native competing vegetation. They argue that although native systems are usually relative stable, they can be disrupted to produce outbreaks of desirable natural enemies. These outbreaks can be grouped in two general categories [63,64]: graded and eruptive. Graded outbreaks arise and subside within well-defined geographical boundaries and do not spread to less-susceptible areas while eruptive outbreaks have the potential to spread over vast areas in a wave-like motion and therefore are of particular interest for biological control. The most practical approach for triggering an eruptive outbreak of such a biological control agent is thought to be a combination of release of the agent and disruption of its naturally occurring enemies [62].

## 6. Exotic Candidate Insects for Introduction in a Neo-Classical Biological Control Programme

### 6.1. *Altica himensis*

*Altica himensis* Shukla (Col., Chrysomelidae) is a flea beetle native to the Kumaon Himalayas in India [65] that has been shown to be an important herbivore of *Rumex hastatus* D. Don [66]. During the dry season its feeding is confined to this species; however, after the rains, the beetle shifts to feeding on a number of herbaceous species to take advantage of the luxuriant growth produced in response to the rains [65].

### 6.2. *Gastrophysa atrocyanea*

*Gastrophysa atrocyanea* Motschulsky (Col., Chrysomelidae) is distributed over a wide area, having been recorded throughout China and from parts of Japan, Korea, the former Soviet Union and Vietnam [67]. Of the 40 or more species of insects feeding on *Rumex obtusifolius* in Japan, it appeared to be the most promising agent for biological control, although Naito [68] suggested that it would be unlikely to give complete control on its own. Like the European species *G. viridula*, *G. atrocyanea* is oligophagous, feeds externally on the foliage and can cause considerable damage to the weed in spring [69]. However, unlike *G. viridula*, *G. atrocyanea* is univoltine [70] and does not persist throughout the growing season in its native habitat.

Field observations in China indicated that *G. atrocyanea* caused a progressive decline in natural *Rumex japonicus* L. populations. Thus it was recommended as a possible control agent for this weed [67].

Studies on *G. atrocyanea*'s biology, host specificity and effects on *Rumex* have been conducted in China and Japan [68,71,72]. Tests showed that the beetles typically dispersed over an area with a radius of almost 50 m around the release point, although some individuals were recovered up to 106 m from it. Based on these findings, it was concluded that overwintered adults would require two release points per hectare in virgin grassland or in habitats with low population densities. In contrast to *G. viridula*, *G. atrocyanea* disperses by both walking (crawling) and flying. Flight was observed most frequently around noon on warm, windless days [71]; although Xiaoshui [67] stated that the adults are unable to fly, this may have been meant to apply only to the gravid females as noted by Naito *et al.* [71].

*Gastrophysa atrocyanea* has been successfully introduced into an area where it did not previously occur. Releases in the Noto Peninsula, Japan resulted in the rapid establishment, multiplication and spread of the beetle, with populations reaching satisfactory levels within 4 years of release [50].

## 7. European Candidate Insects for Use in Augmentative or Conservation Control Programmes

### 7.1. *Apion* species

The majority of *Apion* weevils found on *Rumex* bore into the flowering stem as larvae during May and June, the resultant adults emerging in July or August. Although several *Apion* spp. have been recorded from more than one subgenus of *Rumex*, *Apion miniatum* Germar, *Apion violaceum* Kirby and *Apion hydrolapathi* (Marsham) (Col., Curculionidae) are principally associated in the UK with the subgenus *Rumex* [73], which contains *R. crispus* and *R. obtusifolius* [6]. The primary host plant of *A. violaceum* is *R. obtusifolius* although it will also attack other species of *Rumex sensu stricto* and is fairly common on *Rumex acetosa* L. [74].

The two dominant species feeding in stems of *R. crispus* in Germany were found to be *A. violaceum* and *A. miniatum*. Both produce short mines within the stem, although they exploit distinctly different feeding positions: *A. miniatum* individuals were found in the lower 10% of the stem and are known to cause galls in the roots, whereas *A. violaceum* occurred all along the stem [75]. Larval records indicated that *A. miniatum* attacks its host plant about 2 weeks earlier (beginning of May in the Bayreuth area of Germany) than *A. violaceum* does. In the same area, densities of *A. violaceum* (mean number of individuals per stem) were four times higher than those of *A. miniatum* and 86% of the *Rumex* stems were attacked by the former weevil species compared to about 50% by the latter [75].

Oviposition by *A. violaceum* in *R. obtusifolius* takes place through the sheath enclosing developing flowers, stem leaves and stem. Larvae migrate downwards to the stem and pass through three larval instars within the host plant. A pupation chamber is mined in the tissue at the periphery of the stem immediately before pupation. In common with the other *Apion* species, *A. violaceum* is univoltine and hibernates from September or October onwards in leaf litter, under logs, etc., or it may be found amongst seed heads of the plant in winter [74]. Over a 4-year study period, there was a parallel decline in stem numbers and mean stem height of *A. violaceum*-infested *R. obtusifolius* at two of the sites studied. However, there was also a concurrent decline in *A. violaceum* numbers and density per stem. It was argued that the stem height might be an important factor in both the attractiveness of plants to ovipositing females and in the survival of larvae, reduced stem height prompting the weevils to look for alternative host plants. The quality of sites for the weevil, as defined by the product of stem numbers and stem height, showed a significant correlation with *A. violaceum* numbers [74].

The same three *Apion* species were found in the Mediterranean area during a survey for control agents for *Rumex pulcher* L. in Australia [76]. They were

among the species judged most suitable for biological control purposes. Preliminary host specificity testing has been carried out on *A. violaceum*. Adults were found to feed on *Rumex* species, *Emex spinosa* L. (Polygonaceae), *Rheum rhabarbarum* L. (Polygonaceae) and *Fagopyrum esculentum* Moench (Polygonaceae) (buckwheat). Eggs were laid on *Rumex*, *E. spinosa* and *Rheum rhabarbarum*, but larvae died in the first instar on *R. rhabarbarum*. Scott [76] mentioned the difficulties of separating *A. hydrolapathi* from the similar *A. violaceum*. He stressed the importance of differentiating these species clearly before considering *A. hydrolapathi* for use in biological control.

At several localities in the Czech Republic, Kohout & Kohoutová [77] observed population decline and mass damage of *Rumex obtusifolius* owing to *A. miniatum*. Based on preliminary observations of weevil rearing they presumed that more than one generation per year should be attained under controlled conditions. Investigation of the various biotypes known to exist [78] may allow the identification and isolation of more damaging biotypes.

### 7.2. *Brachycaudus rumexicolens*

The origins of *Brachycaudus rumexicolens* (Patch) (Hom., Aphididae) are uncertain and its biology undocumented. It was first collected from North America and has been recorded from Eurasia, Africa, North America and Australia since the 1960s associated with plants of the family Polygonaceae [79]. In Australia, feeding by *B. rumexicolens* has been observed to cause widespread death and stunting of *Emex australis* Steinh. [80]. Host plant specificity studies have shown that the aphid develops best on the genera *Rumex* and *Emex* and confirmed the Polygonaceae family as the preferred host range [81]. *Lupinus albus* L. (Fabaceae) (white lupin) and *Triticum aestivum* L. (Poaceae) (wheat) were the only plants outside the Polygonaceae on which the aphid showed development similar to that on its usual hosts [81]. It was also concluded that, in Australia, the risk of virus transmission to these important crops would not be increased by *B. rumexicolens* feeding [81]. This aspect of the aphid's biology has not been clarified in Europe although the species was found to be a poor vector for cucumber mosaic virus on lupin [82,83].

Studies of the aphid's development rates revealed a theoretical lower limit for development of 6.4°C and an upper limit of 32°C. Maximum fecundity per day was reached at 19°C, the rate of increase peaking at about 28°C giving a population doubling time of less than 2 days [84]. The species was considered sufficiently safe to use in programmes aimed at augmenting the impact of biological control agents on the weed *E. australis* in Australia [81]. To increase its effectiveness, augmentation by provision of alternative hosts and/or release of mass-reared individuals during the Australian autumn was proposed [84].

### 7.3. *Gastrophysa viridula*

*Gastrophysa viridula* is an iridescent beetle ranging from blue, through green, to almost bronze in colour as an adult, although green is most common. The beetle is oligophagous, the adults occasionally attacking *Rheum rhaponticum* L. [85], but can only complete its whole life cycle on *Rumex*, particularly *R. obtusifolius* [86]. The adult beetles emerge from winter diapause in late spring [87], the timing depending on temperature, and are most often seen on warm sunny days. After mating, the females lay their eggs on the underside of the leaves in batches of about 30 with each female capable of laying up to 1000 eggs in its lifetime of up to 2 months in the field [88]. The bright yellow eggs take approximately 7 days to hatch [89]. The larvae grow and mature quickly, going through three instars, each stage taking about 7 days. Initially the larvae cannot chew completely through the leaves, but by the late second instar are capable of removing all leaf material with the exception of the central midrib and larger veins (I. P. Keary, personal observation). The third-instar larvae eventually leave the plants and pupate in or on the soil, 21–28 days after hatching [87]. The next generation of adults emerges around 7 days later if conditions are favourable and feeds for a few days before mating. This gives an egg to egg generation time of about 35–42 days in the field [87], although this can be reduced to around 28 days in a controlled environment cabinet (I. P. Keary, personal observation). In the wild there are typically three generations per year if sufficient food is available [88] and if the weather is suitable.

The larvae usually aggregate throughout the first instar, dispersing after ecdysis to the second-instar larva occurs, probably to prevent food source depletion [90]. The presence of second- and third-instar larvae deterred adult feeding and oviposition on the same plant because of secretions produced by the larvae [91]. This occurred even when there was an excess of larval food available, although the effect was strongest when larval densities were high and thus may decline with increasing plant size. The deterrent effect continued even after the larvae had pupated and left the plant [91]. This has the potential to create spatial separation between the adults and larvae across an *R. obtusifolius* population.

*Gastrophysa viridula* disperses slowly by crawling, none being observed in flight in a study by Whittaker *et al.* [87]. The mean distance adults moved in this study was 3.0 m (maximum 7.0 m) over the course of 21 days, thus reinvasion of a previously cleared area was slow. Dispersal of adult beetles from a central release point was measured on a diverse vegetation plot [9]. There was active redistribution of the beetles within individual plots (16 × 16 m) but relatively little emigration. Adult beetles in this plot suffered a daily mortality of approximately 12%, mainly through predation. However, observations made during large-scale population outbreaks indicated that the beetle heavily damaged *Rumex* populations across large areas (P. Hann, personal communication). In some types of habitat, *G. viridula* can regularly

achieve these very high population densities and may routinely defoliate the host plant, whereas in other habitats its numbers remain low [88].

Studies on the population dynamics of *G. viridula* in different habitats showed that there was an inverse relationship between the persistence of the beetle population and the diversity and maturity of the background vegetation [9,88]. In mature experimental plots, larval mortality increased, specifically that of the second- to third-instar larvae; there was no effect on egg and first-instar larval mortality [88]. It was concluded that *G. viridula* survives best in plant communities with reduced vegetation diversity. However, it is also important for beetle survival that the field is mowed as this disrupts the development of *Rumex* and prevents the plants flowering and subsequently defoliating simultaneously. Episodic defoliation is important to the beetle as it ensures a consistent supply of food, without which the beetle is unable to achieve its potential maximum of three generations per year [88].

Laboratory studies of the effects of grazing by *G. viridula* showed a greater reduction in the growth of *R. crispus* compared with *R. obtusifolius* [92]. In addition, *R. crispus* responded to grazing with a decrease in its root:shoot biomass ratio, while *R. obtusifolius* responded with an increase. When the two species were grown together in pots in the glasshouse, these effects conferred a competitive advantage on *R. obtusifolius*.

In the field, *G. viridula* grazing resulted in *R. obtusifolius* producing fewer, lighter seeds than ungrazed plants [37]. This may give rise to weaker seedlings with reduced survival owing to diminished competitive ability, although differences in seedling size had disappeared after 4 weeks of non-competitive growth [38].

Cottam *et al.* [93] found that the effects of interspecific competition alone significantly reduced the leaf area, total leaf dry weight, total petiole dry weight, total root dry weight and total rosette dry weight of *R. obtusifolius*. Grazing by *G. viridula* had no effect on the growth of non-competing plants, but significantly reduced the leaf area, leaf dry weight and petiole dry weight of *R. obtusifolius* competing with *Lolium perenne*, acting in synergy with the effects of competition [93].

The rust fungus *Uromyces rumicis* (Schum.) Wint. (Uredinales, Pucciniaceae) infects leaves of *R. crispus* and *R. obtusifolius* mainly between August and October. Feeding by *G. viridula* and *U. rumicis* infection reduced leaf area and plant biomass when the species were used independently, the effect being greater on *R. crispus* than on *R. obtusifolius*. Herbivory and infection produced an additive effect when the species were used together [94,95]. 'Additive' was defined by Hatcher [96] as an interaction that causes a reduction in a plant variable equivalent to that obtained by adding the damage caused by the agents acting independently.

Increased nitrogen fertilization did not enable the plant to escape the effects of the insect or fungus in terms of percentage damage, although the plants were larger in terms of absolute size [97]. However, *G. viridula* fecundity and feeding were reduced by high levels of nitrate, but there did appear to be an optimum level of added nitrogen to maximize the success of the plants [98].

Mass rearing *G. viridula* is quickly and easily established because of the species' high reproductive rate (30–40 eggs per day) and its generation time of only 4 weeks. High relative humidity is essential for survival of the larvae. The rearing of the larvae is possible on a semi-synthetic diet, with the leaf powder of *R. obtusifolius* being the major ingredient. A diet made from air-dried leaves allowed male beetles to develop normally, but there was a strong disturbance of oogenesis in females, which was not observed when freeze-dried leaves were used [99]. The influence of adult feeding on sexual maturation and oogenesis in *G. viridula* has been studied by Scheiwiller & Benz [100].

#### 7.4. *Hypera rumicis*

The biology of *Hypera rumicis* L. (Col., Curculionidae) in Europe is not documented. In a US study by DeGregorio *et al.* [101] the addition of *H. rumicis* to caged *R. crispus* resulted in the loss of stem and leaf tissue and the elimination of seed production. High levels of regrowth and correspondingly high evapotranspiration were observed in *R. crispus* plants previously defoliated by this weevil. It was hypothesised that regrowth may be limited in the field owing to increased competition from the sward, with the increased evapotranspiration exacerbating such stress, particularly in dry conditions. In field trials in Connecticut in spring/summer 1987, heavily infested plants were not as tall and had lower aerial biomass than lightly infested plants 2–7 m away. No seeds were produced by heavily infested plants and there was no regrowth in either the same or the following year. However, as there was no control population for comparison, this apparent reduction in survival should be interpreted with caution; *R. crispus* is more likely to behave as a biennial or annual than *R. obtusifolius* [6,34]. There was little reduction in seedling growth, although only one adult was added to each plant.

In preliminary tests, the effect of the weevil on the agriculturally important North American Polygonaceae was studied. Feeding by *H. rumicis* on *Rheum rhaponticum* leaf discs, in no-choice tests, resulted in less than 2% leaf area loss. Mating adults and egg masses were observed on both caged and naturally infested *R. rhaponticum*, but no larvae, pupae or cocoons were observed. The majority of larvae feeding on *R. rhaponticum* petioles failed to develop into adults [101].

Piesik [102] found that *H. rumicis* grazed the inflorescence of *Rumex confertus* Willd. resulting in a 30% fall in seed production. This decrease was reflected in reductions in the *R. confertus* population. However,

it is not known whether reductions of this scale would impact on *R. obtusifolius* populations in pasture and meadow environments because of the species' prolific seed production and extensive seed bank.

#### 7.5. *Lixus cribricollis*

The biology and host specificity of a colony of *Lixus cribricollis* Boheman (Col., Curculionidae) originating in Morocco was studied in Australia prior to its release [103,104]. The weevil has a circum-Mediterranean and North African distribution where it is known to attack *Emex spinosa* and *Rumex* spp. Field observations in Europe and Morocco indicated that this weevil has one generation per year before aestivating as an adult [104]. Following aestivation, feeding by adults occurred along the margins of leaves [103], but if food was scarce the whole lamina, with the exception of the midrib, was eaten [104]. One, or occasionally two, eggs were deposited in small pits chewed in the stem, petiole or midrib [103]. Larvae tunneled in the stems and the top one centimetre of the taproot. Under heavy attack *Emex* plants collapsed, and in some cases eventually died [104]. Numerous larvae could be found in the same stem and some cannibalism was observed [104]. Larval development was completed in 23–25 days in the quarantine laboratory; pupation occurred within a chamber in the hollowed-out stem, which was normally sealed at both ends with plugs of frass [104]. The duration of the pupal stage was 9–10 days giving an egg to adult time of 40 days [103].

Forty species of plants from 17 families were exposed to sexually mature *L. cribricollis* adults. *Rumex crispus*, *Emex australis* and *E. spinosa* were shown to be the only satisfactory hosts [104]. Normal feeding and occasional oviposition were observed on some other plants within the Polygonaceae, including the minor crops rhubarb (*Rheum rhaponticum*) and buckwheat (*Fagopyrum esculentum*), but almost invariably larvae died before completing the first instar [104].

Weevils were reared in the Australian quarantine laboratory at 22–25°C, with a 16 h day/8 h night. Five cages each containing 15 mature adults on three *E. australis* plants produced a mean of 64 adult progeny per cage [104]. About 800 adults were released in different Australian states for the control of *E. australis*. According to Julien & Griffiths [50], the weevil did not become established so there is no data on its success in controlling either *Emex* spp. or *R. crispus*.

#### 7.6. *Pegomya nigritarsis*

*Pegomya nigritarsis* (Zetterstedt) (syn. *Pegomya solennis* [Meigen]) (Dipt., Anthomyiidae) is a gregarious leaf-mining fly that attacks *Rumex* spp. The insect has a European and doubtfully North American distribution and has been recorded as feeding on species of *Oxyria*, *Polygonum* and *Rumex*. A full description of the species with an extensive bibliography is provided by Henning [105].

*Pegomya nigritarsis* larvae can be found from May to November (in the UK) mining the leaves of *Rumex* spp. [106]. There were at least two generations per year in southern France [107], the first generation of adults emerging in April–May from the overwintered pupae. Larvae from the spring generation pupated and aestivated until September when adults emerged to mate and produce larvae that pupated by the end of October.

Egg-batch size varies between host plants and is correlated with leaf size, but the predicted optimal clutch size is three and that is the number most frequently found in the field [106]. Eggs are invariably laid on the underside of the leaf, the larvae from one clutch of eggs all inhabiting the same mine. They complete development inside the leaves over approximately 15 days [107]. It is not unusual for the fully developed mine, located beneath the upper epidermis, to occupy more than 75% of the leaf area [108]. Larvae are able to initiate a new mine in a fresh leaf, but this behaviour is usually associated with large final-instar larvae [107]. When fully grown, the larvae leave the mine and pupate in the litter layer of the soil. There are two immediate effects of the larval feeding on leaf physiology. The first is a dramatic reduction in net photosynthesis per unit area of leaf affected (to 20% of that in healthy tissue) and the second is a significant increase in water loss [108].

*Pegomya nigritarsis* is known to be attacked by different groups of parasitic Hymenoptera throughout its life cycle (e.g. polyphagous ectoparasites, larval endoparasites and pupal parasites) [106,109]. The role of these parasites in the regulation of *P. nigritarsis* populations would need to be established to evaluate the species' biological control potential. *Pegomya nigritarsis* was one of the insects proposed as a biological control agent for *Rumex* in Australia where the fly would have fewer natural enemies [76]. In the laboratory, cage mating occurred successfully and 939 eggs were obtained from 47 females. Although the fly is mainly bivoltine, Scott & Sagliocco [107] thought that 3–4 generations per year could probably be obtained in the laboratory. Host range tests suggested that although *Rumex* spp. are the preferred hosts, a few other Polygonaceae and *Begonia semperflorens* Otto & Link (Begoniaceae) were attacked under laboratory conditions [107], further oviposition tests were thus proposed. The species has also been suggested as a possible biological control agent for *R. confertus* [110].

### 7.7. Sesiid Moths

Four members of this family are known to feed on *Rumex* in Europe. All these species are root feeders; the eggs are laid on the flowering stalks of adult *Rumex* plants, and the larvae hatch and drop to the ground on a silk thread before mining into the root. Two species have been assessed for use in a control programme against *R. pulcher* in Western Australia and it has been concluded that both are suitable for release [111,112].

*Pyropteron chrysidiformis* (Esper) (syn. *Bembecia chrysidiformis* [Esper]) has a central and southern European distribution. In host specificity tests with first-instar larvae [111], the roots of a number of genera within the Polygonaceae were attacked. Larvae died on a range of plants from other families, but survived on *Persea americana* Mill. (Lauraceae), *Helianthemum nummularium* L. (Cistaceae) and *Quercus ilex* L. (Fagaceae) although the larvae fed on the stems rather than the roots of *Q. ilex*. However, survival of *P. chrysidiformis* larvae on plants other than *Rumex* was thought to be unlikely to occur in nature [111].

*Synansphecchia dorylififormis* (Ochsenheimer) (syn. *Chamaesphecchia dorylififormis* [Ochsenheimer]) is found in the western Mediterranean region, but is more common in North Africa. Adults emerge from pupae from late spring to summer and live for only 1–2 days, the females having to mate and lay eggs during this time [113]. A female moth can produce up to 300 eggs, usually laying between five and seven on dry flowering stems of species of the subgenera *Rumex* and *Acetosa* [113]. Larvae hatch 10–14 days later and descend to the ground on a fine silk thread and mine into the taproot, feeding there for over 12 weeks and growing to about 20 mm long [113]. The number of instars and the duration of pupation are unknown. However, both larval and pupal development are completed inside the plant, below ground.

The two species only have a small area of overlapping distribution in the western Mediterranean, which indicates different climatic preferences. *Synansphecchia dorylififormis* is restricted to a Mediterranean climate whereas the range of *Pyropteron chrysidiformis* extends into temperate zones. They were thought to have the same potential for the control of *Rumex* in Australia [112].

Resynchronization of the one-year life cycle from northern to southern hemisphere conditions was accomplished in *S. dorylififormis*, but was unsuccessful for *P. chrysidiformis*, therefore only *S. dorylififormis* was deemed suitable for continued use in the control programme [113].

Vast numbers of moths were reared for release using a bulk-rearing method. The larvae were raised on pieces of plant root, a method that is distinctly different from the more intensive mass-rearing methods that use artificial diets. Up to 1992, more than 200,000 larvae had been released on more than 40,000 plants at 39 sites in Western Australia. Another 46,000 larvae had been distributed to Victoria, New South Wales and South Australia. *Rumex* plants within the release sites were mown or pruned to expose a short tuft of stems close to the crown. Larvae were applied onto the cut plants using a fine brush. However, this method proved unsatisfactory as moth establishment was found to be low [113]. A new method was developed for releasing the eggs directly into the field. The eggs are quite robust and it was found that they could be glued to a cocktail stick, with approximately 25 eggs per stick, by an

automated machine designed specifically for this task. Each of these 'egg-sticks' was then inserted directly into the cut flower stems of *R. pulcher* [113]. It was found that approximately 1000 plants had to be inoculated in this way if the moth was to become established in an area [113].

The subsequent release and monitoring programme, as reported by Fogliani & Strickland [114], found that *S. doryliformis* has persisted at 70% of the release sites, the moths dispersing 4 km from the release sites during the 7-year study. The impact on *Rumex* populations has varied between sites, with the total reductions observed varying between 37.4% and 100% [114].

Two other sesiid species that occur on the Balkan peninsula have been observed feeding on *Rumex* (I. Toveski, personal communication). *Pyropteron minianiforme* Freyer is found throughout Greece, in the southern parts of the former Yugoslavia and Albania and in northern Turkey. It is a relatively common species on dry slopes and steppes but most frequent in ruderal biotopes in southeast Europe. The adults occur from the end of May to August. Eggs are laid on the dried, seed-bearing stems of *R. crispus* (but also on *R. pulcher* and *Rumex hydrolapathum* Huds., which are endangered species in Switzerland). Larvae bore long canals through the roots, making large lateral galleries and causing heavy damage to the plant.

*Synansphecchia triannuliformis* Freyer is a common species that is adapted to mesic-dry, woody steppes, rocky and sandy areas, roadsides, railway embankments and forest margins. This species coexists geographically with *P. minianiforme* in the Balkans but is also found further north into Austria and southern Poland. There are also isolated populations throughout northern and central Europe. The species produces only one generation per year, the larvae living in the roots of various species of *Rumex*. However, the larger species (*R. crispus*, *Rumex conglomeratus* Murray, *Rumex palustris* Sm.) are preferred. Eggs are again laid on the dried, seed-bearing stems of the host plant. The adults are found from the end of May to the beginning of August.

## 8. Discussion and Conclusions

At the current time, the neo-classical approach to *Rumex* control in Switzerland has to be ruled out, mainly because of acceptability issues. The introduction of exotic organisms for the purposes of biological control is a new concept in Europe [115], despite the numerous successful programmes that have been implemented elsewhere in the world (see Julien & Griffiths [50]). Therefore, any proposed introduction would have to give demonstrably clear benefits and impose minimal risk to other native species to overcome public opinion and legislative restrictions [115]. As several European countries count *Rumex* species among their highly endangered plants (*Rumex rustris* Le Gall in the UK [116]; *R. hydrolapathum*, *Rumex aquaticus* L. and *Rumex maritimus* L. in

Switzerland [1]), the need to demonstrate the specificity of any proposed agent is increased. However, given some of the intractable and damaging weed problems that exist in western Europe (e.g. *Impatiens glandulifera* Royle (Balsaminaceae) [117], *Fallopia japonica* [118]), it seems likely that classical biological control is a topic that will continue to generate debate; for example, Shaw [115] has identified ten species in the UK that are good targets for biological control. If current opinion were to change, the neo-classical approach to *Rumex* control should be reconsidered, and if the analysis were positive, a full risk-benefit assessment of potential candidates conducted.

Inundative and augmentative methods using native insects are often limited by the costs of producing the necessary numbers of control agents [49]. In addition, if very large numbers of insects are required, the agent chosen must be suitable for mass rearing. The costs of development of such a programme and continued production for repeated releases in western Europe are likely to rule out any approach that requires a complex and specialized rearing and distribution programme. One exception to this may be the aphid *Brachycaudus rumexicolens*, rapid population increase being a characteristic of these insects, enabling mass rearing to be quick and efficient [84]. It has been suggested that provision of alternative host plants and/or augmentative releases may be sufficient to promote populations levels that will give control of *Rumex* and *Emex* spp. in Australia [84]. However, the propensity for *B. rumexicolens* to attack wheat and the fact that its role in virus transmission in Europe is unknown mean that it would be unlikely to be a popular choice for augmentation among the Swiss farming community.

Although the Australian programme, using localized inundative releases to establish the southern European sesiid moth *Synansphecchia doryliformis*, appears to have been successful in several areas, this success could not be repeated with the more northerly distributed *Pyropteron chrysidiformis*. Unfortunately, the restricted southern Mediterranean distribution of *S. doryliformis* [119] makes it unlikely that it will be suitable for use in Switzerland. (This is also the case for the weevil *Lixus cribricollis*, which has been evaluated for use in Australia against *Emex* spp. and *R. crispus* [104].)

The major obstacle to the use of *P. chrysidiformis* in Australia was that its life cycle could not be successfully manipulated to guarantee the concurrent emergence of male and female moths during captive rearing [113]. Owing to the species' short life span, this meant that the number of eggs required for mass rearing could not be produced. Although manipulation of the moth's life cycle would not need to be as drastic for use in a European control programme, synchronization of emergence remains a key requirement for population build up to levels necessary for an effective release. Therefore it appears likely that the two other European sesiid species referred to above, *Synansphecchia triannuliformis* and *Pyropteron*

*minianiforme*, would also have to be assessed for use, rather than utilizing existing and proven protocols, thus increasing the costs of the project. In addition, the primary target for the control programme in Australia was *R. pulcher* [113], which typically occurs in very dense patches. The recommendations for the release of *Synansphaecia doryliformis* suggest that there must be at least 0.5 ha of infested land with ten plants per square metre if a release is to succeed [114]. Such a high density is not often associated with *R. obtusifolius* in Switzerland and this may further inhibit the usefulness of the sesiid moths as control agents in Europe.

Habitat and environmental considerations are obviously important to the success of any control programme. In the grassland systems of Switzerland where *R. obtusifolius* is a major weed, the use of any biological control agent must also be able to interface with existing management practices. This may limit the use of many species; for example, Fogliani & Strickland [114] recommend that any areas in which the sesiid moth *Synansphaecia doryliformis* was released should be left undisturbed (preferably fenced) for 2 years to allow the moth to breed and become locally established. These limitations would also apply to all the sesiid species discussed above and other species that exploit the flowering stems, such as the *Apion* weevils.

*Apion* weevils require the flowering stems of the plant to be left in place long enough for weevil development to occur. This would again be problematic, as it would allow the weed to set seed, something that most farmers are keen to avoid (F. Strasser, personal communication). The *Apion* weevils were rejected for use in an augmentative strategy because of this management-related concern coupled with doubts that the damage caused by these species would be sufficient to effect control.

It is partly because of problems of cost and potential efficacy that biological control strategies based on manipulating existing native enemy species as agents of native pests have received little attention to date, compared to other approaches [50,62,120]. Such strategies are often mentioned in weed biological control reviews, but reasons for their success or failure are either not evaluated or not reported at all [56]. However, there is increasing experimental as well as observational evidence that native insect herbivores can control plant abundance and distribution, and interest in the use of native agents is growing (e.g. [52,121–125]). A number of recent publications have attempted to develop a theoretical approach for exploiting the potential of native agents in biological weed control (e.g. [56,62,126]). As already outlined, natural outbreaks that result in rapid herbivore population growth and subsequent damage to the plant hosts have been repeatedly observed under natural conditions [62]. The propensity of *Gastrophysa viridula* to undergo this type of outbreak has been reported in an anecdotal fashion by farmers and scientists (P. Hann, P. E. Hatcher, personal communications). Therefore, *G. viridula* is

the obvious candidate for this type of approach. *Hypera rumicis* occupies a similar feeding niche, but has not been observed to undergo outbreaks in the field. *Pegomya nigritarsis* populations are also likely to be too low to cause sufficient damage to *R. obtusifolius*, and the fly is not present throughout the growing season so would not damage the weed for a sustained period.

As well as occurring at high densities, *G. viridula* is easy to recognize and rear, and individual farmers could feasibly breed beetles for use on their own farms, either indoors or on protected patches of the food plant. This will reduce the necessity for large-scale centralized rearing and, if this should be needed, the beetle's high reproductive rate [88] and unspecialized requirements (I. P. Keary, personal observation) would facilitate this at minimum cost.

*Gastrophysa viridula* is also suited to use in managed pastures. Previous work has shown that the prevention of synchronized flowering means that all the plants in a field do not defoliate simultaneously following anthesis, providing a continuous food supply [9]. However, this is offset by the fact that mowing may interfere with the life cycle of the beetle if carried out when eggs, larvae or gravid females are present. Eggs and larvae would be unlikely to survive the extended period that followed mowing without food, and gravid females would probably be past their peak reproductive capacity by the time sufficient leaf material was again available for successful oviposition to occur. Therefore, it is important that the strategy for enhancing beetle populations is integrated with the land management regimes that are applied. Early data suggest that the beetle benefits from uncut areas, which act as overwintering sites and refugia for adults during the summer [127], although how long a given area could be left unmanaged and yet remain beneficial, if flowering synchronization started to occur, is unknown.

Further information is required regarding the factors that contribute to the observed outbreaks of *G. viridula* and what causes them to subside. Studies are currently in development in Switzerland, Austria and the UK to address these questions and determine whether *G. viridula* can be developed into a management tool for *R. obtusifolius*.

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