Biological control of invasive non-native weeds: An opportunity not to be ignored

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The ecological and economic impacts of invasive species are significant and diverse in nature. Globalisation has led to increased introduction and establishment rates of invasive species in Europe, a trend which is likely to continue. The management of invasive weeds in Europe currently relies on chemical and manual methods which can be costly and environmentally damaging. Classical biological control (biocontrol) is proposed as a safe, cost effective, long term alternative/complementary method. The advantages of weed biocontrol have been documented across the world. This paper provides case studies of invasive weed biocontrol with examples including rubbervine, water hyacinth and leafy spurge. The paper demonstrates that Europe is lagging behind other regions in terms of biocontrol with only one example of a classical biocontrol release against an invasive weed. In 2010, following a thorough research programme, the first classical biocontrol release against a weed in Europe was conducted to manage the invasive, non-native Japanese knotweed in the United Kingdom. Further research is ongoing towards biocontrol of Himalayan balsam and floating pennywort, amongst others. An EU programme is underway to raise awareness of invasive species and assess management techniques, and includes trials to demonstrate the biocontrol of water fern at various locations including sites in The Netherlands. More European countries have started to show interest in this non-commercial control method and are advised to invest in existing weed biocontrol development and utilisation opportunities.

Introduction

Impact of invasive non-native weeds

McNeely *et al*. (2001) define an invasive non-native as 'an alien species whose establishment and spread threaten ecosystems, habitats or species with economic or environmental harm'. The ecological and economic impacts of invasive non-native weeds worldwide are significant and diverse in nature. Invasive non-native plants can impact upon biodiversity, infrastructure, ecosystem functioning, agriculture, leisure and human health (McFadyen 1995, Manchester & Bullock 2000, Charles & Dukes 2007). Although it can be challenging to effectively quantify the ecological impacts of invasive non-natives, various studies have focused on calculating the economic impacts of these species. For example, Pimentel *et al*. (2001), estimate that invasive species cost the United States US$ 134 billion per year (= € 104 billion). The cost of invasives to Europe as a whole has been estimated to be € 20 billion per year (Kettunen *et al*. 2008) and at a country level £ 1.7 billion (= € 2 billion) annually for the UK (Williams *et al*. 2010) and €1.3-2.2 billion for The Netherlands (Van der Weijden *et al*. 2005). Pimentel (2002) estimates the total loss to the world economy as a result of invasive non-native species to be 5% of annual production. With ecological effects additional to these financial costs, it is clear that the impacts of invasive species are of great significance.

Options for management of invasive weeds

Management is often essential to lessen the impact of invasive species. Various tools are available to control invasive weeds, however chemical herbicide use is becoming less acceptable worldwide and manual control methods are often impractical and expensive. In the EU in particular, restrictions on herbicide use in or around water bodies and a current lack of alternative options mean that manual control methods tend to be employed against riparian and water weeds, often at great expense. For example, the mechanized and manual removal of water hyacinth (*Eichornia crassipes*) from Spain's Guardiana

1. Rubber vine, *Cryptostegia grandiflora*, smothering native palm. Photo: Harry Evans
1. *Cryptostegia grandiflora* overgroeit inheemse palmbomen.

2. *Maravalia cryptostegiae* urediniospores. Photo: Harry Evans
2. Ongeslachtelijke urediniosporen van de schimmel *Maravalia cryptostegiae*.

basin between 2006 and 2012 cost € 21.7 million and now requires ongoing vigilance to deal with outbreaks emerging from missed plants, fragments and seeds (Cifuentes y de la Cerra 2012). The requirement for repeat treatment and monitoring of manually cleared sites is apparent for many aquatic invasives, with many exhibiting clonal growth and multiplication as well as sexual propagules (Santamaría 2002). These traits enable plants or seeds missed by manual treatments to recolonise quickly and can assist with dispersal (Santamaría 2002).

An alternative, effective, self-sustaining, environmentally benign and economically acceptable approach for the control of invasive weeds is, therefore, desirable. Biological control (biocontrol) aims to meet these criteria and has a good track record of doing so (Cruttwell MacFadyen 1998), particularly in countries that show a strong commitment to biocontrol research (Culliney 2005).

Biological control of invasive non-native weeds

Biological control has been defined as 'the actions of parasites, predators, and pathogens in maintaining another organism's density at a lower average than would occur in their absence' (De Bach 1964). The natural enemies of the target pest are known as 'biological control agents' (BCAs). Biological weed control has a simple premise; that the addition of phytophagous natural enemies into a system impacted by a weed will suppress the target plant below a desired threshold, be it ecological or economic. The level of suppression required and the type of BCA are dependent on the system. A temporary elevation of a naturally occurring insect or pathogen is more suited to the agricultural/glasshouse environment where the crop to be protected is, by definition, temporary, and permanent agent establishment is neither necessary nor desired. This type of control is known as inundative or augmentative biocontrol.

Biocontrol is practiced against a range of pest species, particularly invertebrates and plants. This paper will focus on the biocontrol of weeds, although the majority of the principles and aims of biocontrol are universal, aiming to find a specific and effective BCA to manage a particular target pest.

Application of classical biological control

If a weed is exotic and has a wide range, the introduction of a natural enemy from its native range for permanent suppression is preferable and is the premise of 'classical biological control' (CBC). This approach has several advantages:

- Sustainable – once established the control should be self-perpetuating.
- Economical – compared to traditional chemical and manual methods.
- Environmentally-friendly – chemical use is reduced, native species are allowed to recolonise slowly, non-target species are unaffected.
- Safe – there is no user exposure to chemicals that might enter the environment. It only impacts the target weed.
- Large scale – the agent should find the weed within its own eco-climatic range.

Classical biological control has been practiced worldwide for over 100 years with approximately 7,000 introductions (including repeat introductions into a single country) of almost 2,700 species of classical BCA (Cock *et al*. 2010). For weeds, there have been over 1,300 releases of more than 400 agents against 150 target weeds worldwide (Julien & Griffiths 1998, updated to 2010). However, despite European countries being the source of around 425 of these releases, there has been only one officially sanctioned release of a non-native BCA against a weed in the European Union, which was the psyllid *Aphalara itadori* (Shinji) against Japanese knotweed (*Fallopia japonica*) in the UK in 2010 (Djeddour & Shaw 2010, Shaw *et al*. 2011). Although the application of classical weed biocontrol is in its infancy in Europe compared with other regions such as South Africa, Australia, New Zealand and North America (Cock *et al*. 2010), the interest in the region has increased significantly in the last decade (Shaw 2003, Sheppard *et al*. 2006, Cock & Seier 2007, Cortat *et al*. 2010). At a

3. Water hyacinth *Eichhornia crassipes* flower. Photo: Rob Reeder
3. Bloemen van de water hyacint *Eichhornia crassipes*.

4. Manual removal of water hyacinth in Benin. Photo: Rob Reeder
4. Handmatige verwijdering van waterhyacint in Benin.

time of globalisation with movement of materials around the planet both extensive and increasing, the introduction and establishment of ecologically and economically injurious non-native species to new regions is increasingly frequent (Hulme 2009, Hulme *et al*. 2009). Indeed, Europe has seen its highest rate of introductions in the last 25 years (Hulme 2009). It is perhaps understandable, therefore, that the demand for long term, affordable and environmentally benign invasive weed control shows signs of increase in the international trade hub that is Europe.

There have been a number of economic assessments and reviews of biocontrol programmes (e.g. Perrings *et al*. 2000, McConnachie *et al*. 2003, Van Wilgen *et al*. 2004, Culliney 2005), which if successful can offer an outstanding return on investment. In his review of benefit/cost data for 25 successful weed biocontrol programmes, Culliney (2005) reports benefit/cost ratio estimates ranging from a minimum of 2.3 up to 4,000, demonstrating the potential economic value of weed biocontrol to a country. After an initial research period requiring the bulk of the investment, the aim of a biocontrol programme is to provide perpetual control of the target weed, requiring no further investment and adding value year on year. A modern biocontrol programme is a thorough and rigorous undertaking focused on safety, which follows a series of established steps and protocols to facilitate the selection of a specific and effective BCA suited to the proposed area of release.

Stages in classical biological control

The stages involved in a classical biocontrol programme have been reviewed by Van Driesche & Bellows (1996) and can be summarised as follows:

Initiation of a biocontrol programme Select target weed; determine any conflicts of interest; review literature on target weed and natural enemies.

Surveys in introduced range Conduct ecological surveys to determine natural enemy-host associations; visit herbaria to trace introduction history and pathways; ensure that any agent already introduced is not considered for further study.

Foreign exploration Establish dialogue with organisation/government(s) in the native range of the target weed; gain permission for survey and export of live native organisms with special reference to the Convention on Biological Diversity; carry out surveys for potential agents across seasons and geographical range including collections from closely-related plants; collect and identify natural enemies using appropriate specialists as necessary; invoke Koch's postulates to identify causal agent(s) of any observed disease; prioritise those species which have potential as BCAs.

Ecology of the target plant and its natural enemies It is useful to compare the ecology of the weed in its introduced and native ranges. The ecology and climatic requirements of potential biocontrol agents should also be investigated to assist in choosing those with high potential impact and to help design release strategies.

Host specificity studies The requirement that a BCA is host-specific is a longstanding one, and practitioners have developed thorough host specificity testing methods. The determinants of host specificity include physical, chemical and nutritional factors which are assessed by host range studies in the field and laboratory and include 'no choice',' choice', 'development' and 'oviposition' tests for arthropods and host susceptibility, infection parameter and pathogenicity tests for pathogens carried out in optimal conditions under the precautionary principal. Host range studies are conducted on a range of plants selected specifically for the country aiming to introduce a BCA, with the plants selected forming the 'test plant list'. Aside from finding a potential BCA to test, the compilation of the test plant list is a fundamental element in a CBC programme. The species included in the list are used to evaluate and confirm the host specificity of the BCA ensuring safety in the proposed release environment and are selected based on morphological and more recently molecular phylogeny (Briese 2005). In summary, the most closely related species in the area of introduction are the most likely to be attacked by an insufficiently specific BCA so this group is prioritized and then other more distantly related species are considered under what is known as the 'centrifugal phylogenetic method' (Wapshere 1974).

5. Japanese knotweed growing by a road in England. Photo: Richard Shaw.
5. Japanse duizendknoop langs een weg in Engeland.

6. Japanese knotweed psyllid *Aphalara itadori* adult, 2 mm length. Photo: Richard Shaw
6. Volwassen bladvlo *Aphalara itadori* op Japanse duizendknoop (2 mm).

7. *Stenopelmus rufinasus* weevil adult on *Azolla filiculoides*. Photo: Rob Reeder
7. Volwassen snuitkever *Stenopelmus rufinasus* op groot kroosvaren *Azolla filiculoides*.

Release and monitoring Once all of the research has been completed, a dossier is produced for consideration by the competent authority. The decision to release is never made by the researchers involved; instead they act as 'honest brokers' in the process. In parallel to the safety studies, consideration should have been given to how the post release monitoring programme will be implemented and pre-release benchmarking can be achieved. For Europe in general a form of risk assessment process is applied to the petitioned agent. The form of monitoring required may be specified by the authorities but ideally should be considered part of the whole programme and budgets included in the initial costing. This is essential if the success or failure of the release is to be gauged and any non-target impacts observed.

Examples of biocontrol in action

There are many examples of weed biocontrol successes (Crawley 1989, Cruttwell MacFadyen 1998, Fowler *et al.* 2000) using arthropod and pathogen BCAs against both terrestrial and aquatic weeds. Success rates of biocontrol programmes vary, though it is telling that those countries investing appropriate resources, time and finances report the highest rates of success (Culliney, 2005). Quantification of BCA impact is important for assessment of the effectiveness of biocontrol programmes (Clewley *et al.* 2012). A recent meta-analysis of 61 published studies of weed biocontrol reports that on average BCAs significantly reduce target plant density, size and mass as well as flower and seed production and that non-target plant density increases at BCA release sites (Clewley *et al.* 2012). Here we present several examples of successful CBC.

Rubber vine (*Cryptostegia grandiflora*)

This vine, native to Madagascar, was introduced to Australia in the 19th century as an ornamental plant, but went on to become highly invasive (Tomley & Evans 2004). Rubber vine grows rapidly and in Australia infested riverine systems, formed dense thickets across pastureland and smothered trees as high as 30 m (McFadyen & Harvey 1990) (figure 1). Chemical and manual control methods were not sufficient to check the progress of *C. glandiflora*, which spread to cover 40,000km^2 at its peak (Tomley & Evans 2004) and had been described as the single biggest threat to natural ecosystems in tropical Australia (McFadyen & Harvey 1990). In the 1980s investigation into biocontrol of this species was initiated. The leaf-feeding caterpillar *Euclasta whalleyi* Popescu-Gorj & Constantinescu from Madagascar, was released between 1988 and 1991 and initially seemed not to establish (McFadyen & Harvey 1990, Mo *et al.* 2000), but has since been found widely across the range of *C. grandiflora* (Mo *et al.* 2000). Due to the ongoing spread and impact of rubber vine an additional BCA release was made in 1995, this time of a pathogenic rust fungus, *Maravalia cryptostegiae* sourced from Madagascar (figure 2). This pathogen has had a huge impact on *C. grandiflora*, causing defoliation, seedling and shoot dieback, reduced flowering, reduced seed production and high levels of mortality across the introduced range of the plant (Tomley & Evans 2002, Tomley & Evans 2004), reducing its financial and ecological impacts.

8. (a) Pond infested with *Azolla filiculoides* in Surrey. (b) The same pond approximately one month later following weevil activity. Photos: Corin Pratt & Sonal Varia
8. (a) Vijver met zware begroeiing van *Azolla filiculoides* in Surrey (UK). (b) Dezelfde vijver ongeveer een maand na snuitkevervraat.

Water hyacinth (*Eichhornia crassipes*)

This free-floating water plant, native to South America is prevalent around the globe as an invasive weed (Julien 2001, Villamagna & Murphy 2010) (figure 3). *Eichhornia crassipes* exhibits both sexual and asexual reproduction and is found predominantly in tropical and sub-tropical waterbodies in more than 50 countries across five continents (Villamagna & Murphy 2010). The plant has significant ecological and economic impacts, for example affecting water quality, ecological communities, recreation, evapotranspiration, agriculture and fisheries (Harley 1990, Villamagna & Murphy 2010). Control using herbicides can offer limited success, but is expensive, requires repeat treatments and is environmentally damaging (Harley 1990). Manual control can be useful for small infestations of water hyacinth, but is limited by scale and is likely to require ongoing monitoring and removal (Harley 1990) (figure 4). Biocontrol research for water hyacinth was initiated in the 1960s and has led to the release of a series of arthropod species from the native range of the plant (Harley 1990). The weevils *Neochetina bruchi* Hustache and *N. eichorniae* Warner and the moth *Niphograpta albiguttalis* (Warren) in particular have been released widely (Julien 2001). Successful biocontrol of water hyacinth is apparent in a number of locations worldwide including regions in Argentina, Australia, India, USA, Africa and Thailand (Harley 1990, Julien 2001). Where biocontrol success has been less clear-cut, integrated control methods are encouraged, with the implementation of BCAs as the base component of all strategies (Julien 2001). Research into additional BCAs that could complement control provided by released agents also continues and led to the recent release in South Africa of the water hyacinth

9. Himalayan balsam infestation on the river Torridge, Devon, UK. Photo: Rob Tanner
9. Uitbraak van reuzenbalsemien langs de rivier de Torridge, Devon, Verenigd Koninkrijk.

specialist grasshopper, *Cornops aquaticum* (Bruner), a South American native (Bownes *et al*. 2010, King & Nongogo 2011). Pathogen attack on *E. crassipes* has also been reported in both the introduced and native range of the plant and is the subject of further investigation (Hill & Cilliers 1999a, Evans & Reeder 2001). Where successful, biocontrol of *E. crassipes* can offer significant economic benefits. For example, in Southern Benin biocontrol of water hyacinth initiated in the 1990s yielded an estimated benefit cost ratio of 124:1 by 2003 (De Groote *et al*. 2003).

Leafy spurge (*Euphorbia esula*)

This herbaceous perennial species native to Eurasia was first introduced to North America in the 19th century, though the original (and subsequent) modes of introduction are subject to some speculation (Dunn 1985). *Euphorbia esula* forms extensive root networks, can reproduce vegetatively and is a prolific producer of seed; traits which enable the plant to outcompete native vegetation and infest rangelands, pastures, waterways, roadsides and cropland (Noble *et al*. 1979) and which have facilitated its spread throughout Canada and the plains of the United States. In addition to economic losses through lost crop and cattle forage production caused by *E. esula*, millions of dollars have been spent annually on chemical control of this weed (Nowierski 1989) prompting investigation into the potential for its biocontrol. The leafy spurge found in North America is actually a species complex comprising multiple subspecies and/or hybrids following multiple introductions, which adds complexity to the possibility of control (Bourchier *et al*., 2006). The first BCA released against *E. esula* was the leafy spurge hawk moth *Hyles euphorbiae* (Linnaeus) from Europe in North America in 1965. There have since been further insect BCA releases against the weed, with 12 species released in total (Bourchier *et al*. 2006). Many of these BCAs also attack the invasive congener Cypress spurge, *Euphorbia cyparissias* and have been employed to enhance control of both weeds. The impact of the insects varies across sites and regions, but the array of BCAs available now make up an essential component of integrated pest management strategies against leafy spurge (Bourchier *et al*. 2006, Lym 1998), reducing reliance on herbicides. The gross annual economic benefit of biocontrol of leafy spurge in the northern Great Plains of the United States alone has been estimated to reach US$ 58.4 million by 2025 (Bangsund *et al*. 1999).

Weed biocontrol in Europe

Though weed biocontrol in Europe has historically been low in comparison with regions such as Australia, South Africa and North America (Cock *et al*. 2010), there has been a significant increase in interest and investment in recent years (Shaw 2003, Sheppard *et al*. 2006, Cock & Seier 2007, Cortat *et al*. 2010). Europe is home to an array of damaging invasive non-native weed species thought to be ideal candidates for biocontrol (Sheppard *et al*. 2006). Additionally, pressure to meet the EU Water Framework Directive requirement of achieving 'good ecological status' of all water bodies by 2015 means that EU countries will have to manage their worst aquatic and riparian weeds. Several invasive riparian/water weeds have, therefore, been prioritised for biocontrol research in Europe. The current status of these programmes is as follows:

Japanese knotweed (*Fallopia japonica*)

This fast-growing herb native to Japan is invasive in a number of regions worldwide including North America, Australia, New Zealand and much of Western Europe (figure 5). *Fallopia japonica* is a rhizome-forming perennial that dominates invaded sites, reducing the quality of riparian habitats and impacting upon biodiversity (Gerber *et al*. 2008). Japanese knotweed can also cause significant and costly damage to infrastructure (Djeddour & Shaw 2010). The annual cost of Japanese knotweed to Great Britain alone has been estimated at € 215 million (Williams *et al*. 2010). Outside its native range the plant does not rely on seed, but grows clonally from rhizome fragments (Bailey 1994, Seiger & Merchant 1997) that are readily distributed via water, trade and construction. Adding complexity to the situation is the ability of *F. japonica* to hybridise with giant knotweed, *F. sachalinensis*, to produce *F.* x *bohemica*. This hybrid is thought also to be present in much of the introduced range and able to generate viable seed, though *in-situ* germination in Europe is low

10. *Puccinia komarovii* rust fungus infection on Himalayan balsam leaf. Photo: Rob Tanner
10. *Puccinia komarovii* roest schimmel infectie op een blad van reuzenbalsemien.

11. Himalayan balsam seedling infected with the aecial stage of rust infection. Photo: Rob Tanner
11. Zaailing van reuzenbalsemien geïnfecteerd met aecidia van de roestschimmel.

(Bailey *et al*. 2009). Manual or mechanical removal of Japanese knotweed is time consuming, expensive and often requires repeat treatment to ensure plants and rhizome fragments are not missed. Kabat *et al*. (2006) carried out a systematic review of 65 published knotweed management studies and were unable to conclude long-term efficacy for any control measure. To control Japanese knotweed across Britain using 'traditional' methods would cost upward of € 2 billion (Williams *et al*. 2010). Biocontrol research was initiated in 2000 by CABI on behalf of a consortium of sponsors in the UK, representing government, transport, development, water and environmental divisions. Initial surveys in Japan revealed a suite of natural enemies impacting upon *F. japonica*, several of which were prioritised and subjected to host range testing under Phase 2 of the programme, which began in 2003 and revealed two agents of particular promise. A psyllid (*Aphalara itadori* (Shinji), figure 6) was found to be highly specific. Following testing, consultation and licensing, it was released at a restricted number of sites in Britain in 2010 (Shaw *et al*. 2011). In the current establishment phase releases are being made at 8 sites across England and Wales, and whilst the psyllid has been able to persist and overwinter, populations are yet to increase. A petition was submitted in North America in 2012 for the release of the same species and interest is growing in many other European countries. Work on a leafspot fungus (*Mycosphaerella polygoni-cuspidati*), discovered during the initial surveys to Japan was postponed whilst research focused on the psyllid, but has recently been reinitiated.

Water fern (*Azolla filiculoides*)

This floating aquatic fern native to the Americas has an extensive distribution worldwide and is often considered a weed

12. *Hydrocotyle ranunculoides* invasion in the River Wandle, South London, UK. Photo: Djami Djeddour
12. Uitbraak van grote waternavel *Hydrocotyle ranunculoides* in de rivier de Wandle, Zuid-Londen, Verenigd Koninkrijk.

13. *Listronotus elongatus* weevil adult on *Hydrocotyle ranunculoides* in native range. Photo: Richard Shaw
13. Volwassen snuitkever *Listronotus elongatus* op *Hydrocotyle ranunculoides* in oorspronkelijk leefgebied

(Ashton 1974), although it has a history as a green manure in rice cultivation in Southeast Asia (Hill & Cilliers 1999b). *Azolla filiculoides* hosts a symbiotic nitrogen-fixing cyanobacterium that fulfils the nitrogen requirement of the fern and facilitates its rapid vegetative reproduction throughout the year (Hill & Cilliers 1999b). The fern is also able to reproduce sexually, producing a resistant overwintering spore (Hill & Cilliers 1999b). *Azolla filiculoides* has various impacts where present, including reducing water quality, increasing siltation, reducing water surface for recreation (e.g. boating and fishing), reducing aquatic biodiversity, blocking pumps and reducing water flow in irrigation channels (Hill & Cilliers 1999b). Chemical control of *A. filiculoides* is possible in some countries, but expensive, requiring follow-up (Hill & Cilliers 1999b) and is potentially prohibited by a country's herbicide regulations. Manual control by removal of *A. filiculoides* is impractical on a large scale, with the growth rate of the fern and its ability to multiply from a single fragment, making this a time-consuming, costly and short-term solution (Hill & Cilliers 1999b). In South Africa the biocontrol of *A. filiculoides* was investigated leading to the release in 1997 of a genus-specific weevil, *Stenopelmus rufinasus* Gyllenhal (figure 7) (Hill & Cilliers 1999b). The weevil, native to the USA, had a huge impact on *A. filiculoides* and a review of the fern's status in 2008 revealed that it no longer poses a threat to aquatic ecosystems in South Africa and is considered to be under complete control (Hill *et al.* 2008). The benefit-cost ratio of the programme was estimated to reach 15:1 by 2010 (McConnachie *et al.* 2003).In Europe, *A. filiculoides* is widespread. However, the weevil *S. rufinasus* is also present in a number of countries that have the fern (Fauna Europea 2012). It is likely that the weevil was introduced as a stowaway on *A. filiculoides* that may have been imported as an ornamental or by migratory waterfowl (Janson 1921). In Great Britain, CABI has established a successful initiative (www.azollacontrol.com) rearing and redistributing the weevil to sites infested with *A. filiculoides*, with no restrictions on movement of the weevil due to its status as 'ordinarily resident' having been first identified in Britain in 1921 (Janson 1921). The weevil has been shown to have a dramatic effect on Azolla, often resulting in local eradication of the weed (figure 8).Between 2011 and 2012, The Netherlands *Stichting Toegepast Onderzoek Waterbeheer* (STOWA) funded a pilot project led by CABI to locate and identify *S. rufinasus* in The Netherlands and investigate the potential for its mass rearing and release in the country to control *A. filiculoides*. In addition, under a European Commission Interreg 2 Seas-funded project entitled 'Reducing the Impact of Non-native Species in Europe (RINSE)', CABI aims to conduct further demonstration trials of *S. rufinasus* on *A. filiculoides* in England, France, Belgium and The Netherlands to investigate the potential to rear and redistribute the weevil in mainland Europe for the treatment of water fern infestations.

Himalayan balsam (*Impatiens glandulifera*)

This plant is a fast-growing riparian weed, invasive in Europe, North America, New Zealand and parts of Asia (Cockel & Tanner 2011) (figure 9). The plant is an annual species native to the western Himalayas that produces high numbers of seeds that are scattered by bursting seed pods. *Impatiens glandulifera* has been shown to have a negative impact on native invertebrate populations (Tanner 2012). Sites invaded by Himalayan balsam may also exhibit reduced plant biodiversity (Hulme & Bremner 2006), though this is not always apparent, especially when the percentage cover of the plant is low (Hejda & Pyšek 2006). Manual pulling of *I. glandulifera* can be effective in the short term, but is laborious and must be repeated for several years at a catchment scale to deplete the seed-bank and prevent fresh invasions. Chemical control can be effective in discrete areas, though at a catchment scale, and in areas of high conservation, chemical control is neither practical nor desired. Biocontrol research for *I. glandulifera* was initiated in the United Kingdom by CABI in 2006, funded by several UK stakeholders. Nine surveys to the plant's native range have since been conducted, leading to the prioritisation and host-range testing of several insect and fungal natural enemies. Those species not proving to exhibit a high level of specificity have been eliminated from the research leaving a rust fungus (*Puccinia komarovii*), which causes high levels of damage to the target species (figures 10-11). The full lifecycle of this autoecious rust has been established in quarantine. Research is now focused on completing the host-range testing against 65 closely related plant species. The majority of the test plant list has been assessed and the rust continues to display excellent potential as a BCA of *I. glandulifera* for the UK and other European countries.

Floating pennywort (*Hydrocotyle ranunculoides*)

This floating aquatic perennial is native to the Americas, but has established in northern Europe and Western Australia as an invasive weed. *Hydrocotyle ranunculoides* commonly exhibits vegetative reproduction in its introduced range (Newman & Dawson 1999) and can form dense mats that impact upon navigability of waterways along with native plant and invertebrate species richness (Stiers *et al*. 2011) (figure 12). The ability to reproduce vegetatively from single nodal fragments allows *H. ranunculoides* to recolonize downstream sites rapidly following cutting, making this an unsuitable control method (Newman & Dawson 1999). Manual removal of the plant, as with many water weeds, is an expensive, time consuming process that requires ongoing vigilance and follow-up treatments to provide long-term control (Newman & Dawson 1999). Chemical control can be effective against *H. ranunculoides*, particularly as part of an integrated strategy (e.g. Ruiz-Avila & Klemm 1996) though is a costly, intensive approach that is not an option for many countries suffering from the weed. Additionally, resistance to glyphosate has been observed in the UK (Newman & Dawson 1999). Research into the potential for biocontrol of *H. ranunculoides* is now underway at CABI in the UK. Initial field studies conducted in South America revealed a wide range of natural enemies in the plant's native range including the weevil *Listronotus elongatus* Hustache (figure 13) which showed promise in initial host range tests. Further field studies in the Americas have revealed stem-mining flies and a rust fungus that show good potential as BCAs based upon field observations and literature study.

Conclusion

Europe has seen a dramatic increase in the establishment of invasive species in recent years, including a number of damaging weed species. The financial and environmental costs of invasive weeds are highly significant and whilst management is essential, traditional chemical and manual controls can be expensive, ineffective and environmentally damaging. A safe alternative method of control is available in the form of classical biocontrol, which has been practiced with good success in many regions of the world, but only very recently in one EU Member State: the United Kingdom. Where successful, biocontrol can offer perpetual control and outstanding value and for these reasons interest in this tried and tested technique is growing in Europe. It is clear that European countries affected by serious invasive weeds can no longer afford to ignore this approach and are strongly advised to engage in its research and implementation.

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Samenvatting

Biologische bestrijding van invasieve planten: een niet te negeren mogelijkheid
Invasieve exoten zijn woekerende soorten van elders die de lokale biodiversiteit verstoren en/of economische schade veroorzaken. Invasieve soorten zijn – na habitatvernietiging – de tweede oorzaak dat soorten uitsterven. Daarnaast wordt wereldwijd de economische schade veroorzaakt door invasieve soorten geschat op 5% van de economie. Jaarlijks komen nog steeds, of steeds meer, nieuwe soorten binnen via de handel (zonder risicoanalyse), als ballast en/of op eigen kracht. In Europa is het probleem van de invasieve wateronkruiden bijzonder omdat watergebieden over het algemeen kwetsbaar en biologisch divers zijn. Bovendien is in de Europese regelgeving, Kaderrichtlijn Water, overeengekomen dat naar een goede ecologische status moet worden gestreefd. Chemische bestrijding is vaak wettelijk verboden en mechanische bestrijding is duur. Klassieke biologische bestrijding van invasieve, exotische planten in waterecosystemen is een goed alternatief voor chemische en mechanische bestrijding van deze wateronkruiden. Biologische bestrijding gaat uit van het gebruik van natuurlijke vijanden die de exoot op een natuurlijke manier beperken in groei en ontwikkeling. In dit artikel wordt gerefereerd naar succesvolle biologische bestrijding van invasieve plantensoorten in alle regio's van de wereld. Tot op heden blijft Europe hierin sterk achter. In het Verenigd Koninkrijk wordt sinds 2003 gewerkt aan klassieke biologische bestrijding van Japanse duizendknoop die daar, net als in Nederland en diverse andere Europese landen, grote problemen veroorzaakt, zowel in de natuur als voor bebouwing en infrastructuur. Dit is het eerste voorbeeld van uitvoering van klassieke biologische bestrijding van een invasieve plantensoort in Europa. De resultaten in het Verenigd Koninkrijk kunnen, met relatief weinig extra onderzoek relevant gemaakt worden voor andere Europese landen. Daarnaast wordt gewerkt aan onderzoek naar biologische bestrijding van groot kroosvaren, reuzenbalsemien en grote waternavel. Dit artikel dringt aan op meer aandacht in Europa voor de unieke kans tot internationale samenwerking op het gebied van biologische bestrijding van de meest schadelijke invasieve planten.

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