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POTENTIAL SOLUTIONS FOR THE CONTROL OF RIPARIAN AND AQUATIC INVASIVE WEEDS: A REVIEW ON THE PROGRESS OF CLASSICAL BIOLOGICAL CONTROL PROGRAMMES IN THE UK

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SUMMARY
The impact of invasive alien species on riparian ecosystems can be profound. The UK is leading the research into the biological control of several invasive aquatic and riparian plants common to many European countries. This has recently resulted in the release of the first biological control agent against a weed in Europe. This presentation highlights the status of ongoing research into the biological control of invasive alien species in the UK, with particular reference to Japanese knotweed (*Fallopia japonica*), Himalayan balsam (*Impatiens glandulifera*), floating pennywort (*Hydrocotyle ranunculoides*), swamp stonecrop (*Crassula helmsii*), giant hogweed (*Heracleum mantegazzianum*) and floating fairy fern (*Azolla filiculoides*) in the context of the Water Framework Directive.

Key words: Water Framework Directive, invasive plant species, riparian habitats, biological control.

RÉSUMÉ
SOLUTIONS POTENTIELLES POUR LA LUTTE CONTRE LES PLANTES ENVAHISSANTES RIPARIENNES ET AQUATIQUES: REVUE DES PROGRES POUR LES PROGRAMMES DE LUTTE BIOLOGIQUE CLASSIQUE AU ROYAUME UNI
Les espèces exotiques envahissantes peuvent avoir un profond impact sur les écosystèmes ripariens. Le Royaume-Uni mène la recherche dans le domaine de la lutte biologique contre un certain nombre de plantes aquatiques et ripariennes envahissantes, qui sont un problème commun à d'autres pays Européens. Ces efforts ont récemment abouti au premier lâcher d'un agent de lutte biologique contre des plantes envahissantes en Europe. Notre but est de présenter l'état des recherches pour la lutte biologique des espèces de plantes exotiques envahissantes en Grande-Bretagne et en particulier pour la renouée du japon (*Fallopia japonica*), l'impatiente de l'himalaya (*Impatiens glandulifera*), l'hydrocotyle à feuille de renoncule (*Hydrocotyle ranunculoides*), la crassule de Helm (*Crassula helmsii*), la berce du Caucase (*Heracleum mantegazzianum*) et l'azolla fausse fougère (*Azolla filiculoides*) dans le contexte de la directive-cadre sur l'eau.

Mots-clés: Directive-Cadre sur l'Eau, plantes exotiques envahissantes, zone riparienne, lutte biologique.

INTRODUCTION

WATER FRAMEWORK DIRECTIVE

Riparian and aquatic invasive weeds can have an important impact on the aquatic environment, compromising water quality and potentially altering food chains. The presence of invasive species often leads to a loss in biodiversity, wherever dense monocultures outcompete native plants for environmental resources on the river banks or cause deoxygenation of the water when forming dense mats on the surface. Moreover, the presence of weeds can prevent access to a water body or lead to drowning when mistaken for solid ground. Furthermore blocked channels increase the risk of flooding and riverbanks are left vulnerable to erosion when the plants die-back during the winter leaving the soil bare thereby increasing sediment intake into the river system.

In order to achieve good chemical and ecological status by 2015, the European Union has established a framework for water protection and management (Water Framework Directive, Directive 2000/60/EC), which it aims to attain through reduction and prevention of pollution and deterioration, enhancement and restoration of bodies of water, promotion of sustainable water use, protection of the aquatic environment and ecosystems and mitigation of the effects of floods and droughts.
To comply with the Water Framework Directive (WFD), efforts must be invested to reduce the abundance of invasive weeds and their impact on the environment. There are several methods of control that can be applied against invasive weeds. Chemical control using herbicides can be effective, but is expensive on a large scale and is subject to restrictions when applied close to water and rarely acceptable in most EU Countries. Only one herbicide remains licensed for use on water in the UK, and being non-selective, could damage biodiversity. Manual control methods are available for most invasive weeds, but are labour intensive and expensive.

BIOLOGICAL CONTROL

Biological control uses natural enemies (arthropods or pathogen) that have co-evolved with their host in its native range (DeBACH, 1964). This is ecologically sustained by the Natural Enemy Release Hypothesis, which postulates that the success of alien plant species in their introduced range can be explained by the loss of their natural enemies (JONES & LAWTON 1991, KEANE & CRAWLEY, 2002). Biological control aims to redress this balance by introducing one or more specific enemies from the native range to control the invader in the introduced range.
The use of host specific biological control agents has no negative impact on the environment when used in a correct way. The release can take place with a minimum of disturbance and if the weed is locally eradicated, the agent will die as it cannot feed on any other host. However, this method does not aim to eradicate the target weed, but rather relies on the establishment of the biological control agent in the invasive range and its ability to act in the long term to reduce impact below an ecological or economic threshold. Some weeds can spread vegetatively or by seeds along waterways, thus it is important that the control takes place in the entire catchment to limit further invasion as well as reestablishment in the treated area. Biological control can also be integrated into existing chemical and mechanical management schemes.

Classical biological control has over a century history with more than 1’300 introductions of about 400 species of biological control agents against 130 weeds in 70 countries (JULIEN & GRIFFITHS 1998) Among its successes, CABI counts the use of the rust fungus, Maravalia cryptostegiae in the biological control of the rubber vine weed (Cryptostegia grandiflora) that was introduced from Madagascar in the 19th century as an ornamental garden plant and as a source of latex and the use of two leaf-eating beetles, Galerucella calmariensis and

G. pusilla, in the biological control of purple loosestrife in North America (*Lythrum salicaria*), introduced to the US and Canada from Europe as an ornamental plant.

There is no shortage of weed targets of concern to Europe and SHEPPARD *et al.* (2006) list the top twenty. CABI is currently working on more than two dozen projects of biological control of weeds worldwide, from which six projects on European weeds are presented below as they are relevant to the WFD.

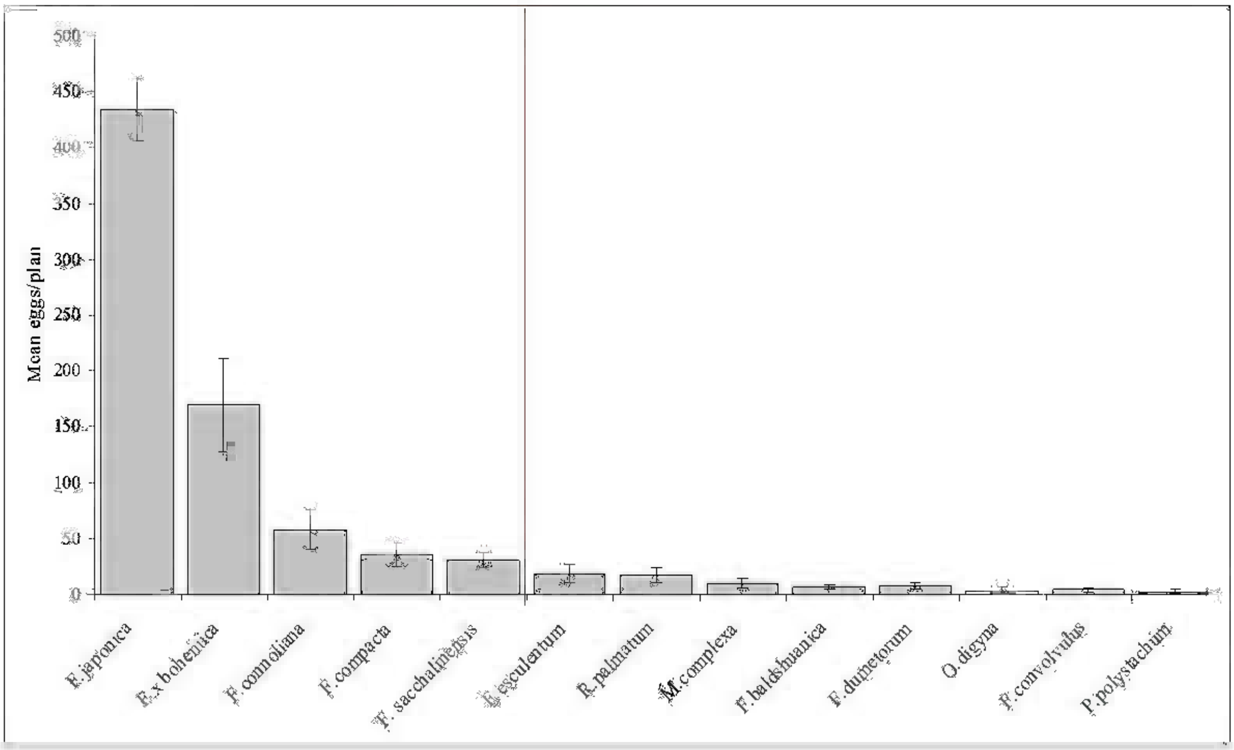
PROJECTS

JAPANESE KNOTWEED

Japanese knotweed (*Fallopia japonica*, Polygonaceae) is a fast-growing perennial originating from Japan that was introduced into the UK in the mid 1800s as an ornamental. Since its escape from gardens, it has spread rapidly across the UK and is currently one of the most damaging invasive weeds. Where it has become established, it often reduces native biodiversity as a result of its ability to outcompete all other vegetation, thus altering the native flora and its associated invertebrate community (e.g. GERBER *et al*., 2008). A recent study suggested that the economic damage to the British economy is greater than £150 M p.a. (WILLIAMS *et al,* unpublished) and it has been estimated that the cost of controlling the species throughout Great Britain would be in excess of £1.5 Bn (DEFRA 2003).

Following preliminary surveys in 2000, a project aimed at identifying a biological control agent against Japanese knotweed began in earnest in 2003, with the support of a consortium consisting of British Waterways, Cornwall Council, the UK Department for Environment, Food and Rural Affairs (DEFRA), the Environment Agency, Network Rail, the South West Development Fund and the Welsh Assembly Government. Seven surveys conducted by UK and Japanese scientists in Japan identified 186 invertebrate species and over 40 species of fungal pathogens attacking Japanese knotweed in its native range. A comprehensive review of the literature coupled with field observations of the invertebrate species, allowed those species that were most likely to be Japanese knotweed specialists to be selected for further study. Susceptibility tests and preliminary host-specificity tests excluded more species and finally, one sap-sucking species, the psyllid *Aphalara itadori* was selected as a potential biological control agent. The species was brought into a licensed quarantine facility in the UK for host-range testing and a test-plant list was assembled using the centrifugal phylogenetic method based on WAPSHERE (1974). This approach assumes that those species most closely related to the target weed are more likely to be attacked than more distantly related species. The resulting test-plant list consisted of 89 species, including all *Fallopia* species and virtually all other species belonging to the Polygonaceae and occurring in the UK, 23 species that have been introduced to the UK, 13 ornamental species and 10 species of economic importance. The results of the host-range tests, undertaken to establish whether the adults lay eggs on other species than the target species and whether the insect can complete its life cycle on other species than Japanese knotweed, are summarised in Fig. 1. Although twelve species other than the target species received a limited number of eggs, complete development was only recorded on invasive knotweeds. This showed *A. itadori* to be a knotweed specialist and to be suitably host-specific as a biological control agent against Japanese knotweed (SHAW *et al*., 2009).

Figure 1 : Mean number of eggs laid per plant in multiple-choice oviposition tests. (Nombre moyen d'œufs pondus par plante lors de tests d'oviposition à choix multiple)



The figure only includes those species which ever received any eggs; the 78 species that did not receive any eggs are not shown. To the right of the vertical line no adults were produced and to the left only invasive knotweeds, varieties or hybrids which could support complete development. Error bars indicate one SE.

Two parallel applications for release of *A. itadori* were submitted to the UK government. A Pest Risk Analysis was submitted to obtain release from the Plant Health quarantine licence, under which it was being cultured, and an application under the Wildlife and Countryside Act was submitted to obtain a license to release *A. itadori* into the wild. Both applications went through a review process that included iterative internal Governmental committee reviews, independent scientific peer review, a three-month public consultation and advice from the Chief Scientist before a ministerial decision to authorise release was taken by the Secretary of State.

In March 2010, the go-ahead was given to release the psyllid. The releases of *A. itadori* were made at a limited number of designated sites that will subsequently be expanded in a phased way. A 5-year monitoring programme was a requirement of the licence and is aimed at recording the impacts of *A. itadori* on Japanese knotweed and the native vegetation and invertebrate community.

HIMALAYAN BALSAM

Impatiens glandulifera (Balsaminaceae), commonly known as Himalayan balsam, belongs to the family Balsaminaceae, which contains circa 850 species, divided into two genera, mainly distributed throughout tropical and sub-tropical Africa, temperate Asia, North America and Europe. The first record of *I. glandulifera* in Europe was from the UK in 1839, where it was first imported for its floristic elegance. Soon after, the plant literally exploded out of the large Victorian gardens, where it was grown as a novel showpiece, to become naturalised in the British countryside by 1855. *Impatiens glandulifera* is now the tallest European annual, commonly attaining a height of 2-3 m (BEERLING & PERRINS, 1993; ANDREWS *et al*., 2005).

As with most of Europe's riparian weeds, current control methods are often difficult to implement, due to the often inaccessible habitats the weed grows in, not to mention labour intensive, expensive and any chemical application being tightly regulated. For Himalayan balsam, repeated control attempts over two or three seasons can exhaust the short-lived seed bank. However, cutting or spraying must be carefully timed early in the season to incorporate all plants at various growth stages and to prevent seed set. Total eradication from an area may be impossible if populations upstream remain untreated. Thus catchment-scale treatments are recommended for this weed, but difficult to implement with traditional methods due to the sheer magnitude of established populations, division of land ownership and costs. The UK Environment Agency has estimated it would cost between £150-300 million to eradicate Himalayan balsam in the UK (Environment Agency, 2003).

A consortium of funders, including DEFRA, the UK Environment Agency, the Scottish Government and Network Rail have funded research into the biological control of Himalayan balsam for the UK since 2006. As an exotic weed *I. glandulifera* should be amenable to a classical weed biological control programme (TANNER, 2008). Over the last four years, scientists from CABI have surveyed the plant throughout its native range (both the Pakistan and Indian region of the Himalayas), identifying natural enemies, which could potentially be used as biological control agents in the plants invasive range.

Surveys were conducted in 2006 in and around the Kaghan valley, Pakistan and in 2008 in the Kullu valley, Himachal Pradesh, India. It was clear that the latter region had a greater diversity of natural enemies on Himalayan balsam than the Pakistan Himalayas, therefore research has since focused in and around the Kullu valley. In collaboration with the National Bureau of Plant Genetic Resources (NBPGR), Pusa, New Delhi, surveys have been conducted throughout the growing season and five natural enemies have been prioritised for further research, based on field observations and research. The five priority species included the three beetle species *Metialma suterella*, *Languriophasma cyanea* and *Alcidodes fasciatus* and two plant pathogens, a *Puccinia* rust and a *Septoria* leaf spot.

After successfully obtaining export of the four of the five potential biocontrol agents from India in June 2010, CABi scientists are currently researching the life cycle, host range and in the case of the *Puccinia* rust, the infection parameters, in CABI's quarantine facility. It is expected that the list of potential agents will be reduced further after the results of current studies and currently the *Puccinia* rust species looks like the most promising candidate.

FLOATING PENNYWORT

Floating Pennywort, (*Hydrocotyle ranunculoides*, Araliaceae), is a perennial semi-aquatic or aquatic plant, which forms dense vegetative mats in still or slow-flowing watercourses. It is considered to be native to both North and South America. The weed was introduced to Europe relatively recently, in the 1980s, through the aquatic nursery trade and has subsequently spread into water bodies in a number of European countries including Belgium, Germany, Italy, the Netherlands, and the UK. In Belgium, the Netherlands, and the UK in particular, it could well be considered as the worst aquatic weed.

Floating pennywort can regenerate from very small fragments and can grow up to 30 cm a day, often doubling its biomass in under a week. This weed has already cost millions of Euros to control in Europe, and increasingly frequent flooding is transporting the plant to new systems.

In 2006/7, limited funding was obtained for a survey in Argentina, part of the native range of *H. ranunculoides*, after collaborators confirmed the presence of a seemingly host-specific weevil. The expedition was carried out in collaboration with the Centre for Ecology and Hydrology (CEH), UK, and the USDA (US Department of Agriculture) South American Biological Control Laboratory (SABCL) during the breeding season of the prioritized weevil *Listronotus elongatus*. The survey was a great success with various natural enemies, both insect and fungal, being observed damaging the plant in various regions of Argentina, where many *Hydrocotyle* spp. exist. The weevil was then subjected to preliminary host-range testing, which indicated that it was a floating pennywort specialist and did not pose a threat to our European native marsh pennywort (*Hydrocotyle vulgaris*). These very promising preliminary findings suggested that biological control could be a serious consideration for any nation facing an invasion of this serious exotic weed. Other agents, including an ephydrid fly and fungal leafspot pathogen, were also be worthy of consideration.

In 2010, the UK government contributed further funds towards the programme in order to specifically address the requirements of the WFD. The project aims to concentrate studies on the weevil (considering other agents in parallel) and to initiate the host range testing of prioritised species against a test plant list appropriate for the UK. Ecological studies and assessments of associated fauna and flora as well as population parameters are also being studied in parallel in the UK and Argentina to provide baseline data and allow “home and away” comparisons to be made. Such comparisons are an important part of any biocontrol programme since they allow researchers to establish that no natural enemies have already been imported with the plant or have become newly associated with the plant prior to any deliberate introductions of biological control agents. The ongoing gathering of useful information on the growth cycle, regeneration potential of the plant throughout the year and the influences of temperature, natural enemies and other abiotic and biotic parameters on populations will also allow to better inform any potential introductions.

CRASSULA

Crassula helmsii (Crassulaceae) is known either as Australian swamp stonecrop or New Zealand pigmyweed and these names indicate its area of origin. The actual introduction is believed to have been from one population in the Murray River (DAWSON *et al*., 1994) though other authors believe it was from Tasmania (CEH factsheet). It was found naturalised in the UK in the 1950s and has spread very rapidly.

Thanks to its wide tolerance of climate and an ability to grow both submerged in relatively deep water and emergent on bank-sides, it can now be found at more than 2,000 sites in the UK. Another advantage it has is an ability to grow throughout the year, with no dormant period, due to a distinct metabolism. It is very difficult to control and can be very costly with the treatment of 500 sites estimated at 1.45 - 3 million Euros (LEACH & DAWSON , 1999).

Following start-up funding from DEFRA, a brief survey was carried out in 2009 in collaboration with Department of Primary industries Australia, University of Tasmania and Landcare Research, New Zealand. Despite the widely-held belief that the plant had no significant natural enemies in its native range, these surveys revealed a suite of both arthropod and fungal natural enemies. This included at least one species of weevil, the larvae of which was found mining the stems of the plant. It is hoped that funding will continue to allow a more thorough survey, guided by the results of some on-going molecular biogeographical studies. This should lead to initial host range testing of the most promising natural enemies against a proposed test plant list.

GIANT HOGWEED

Heracleum mantegazzianum (Apiaceae), commonly called giant hogweed, is a perennial forb which is native to the western Caucasian mountains. From there the plant was introduced into botanical gardens in Europe and North America in the 19th century due to its stunning growth habit of up to 5 m of height and its large showy leaves and flowerheads (PYŠEK, 1994). Initially viewed as an ornamental curiosity, giant hogweed has by now become a widespread invasive weed in most of its introduced range, threatening local biodiversity in affected riparian as well as urban habitats (TILEY *et al*., 1996). In addition to posing a threat to biodiversity, giant hogweed also constitutes a serious public health hazard due to its photosensitizing sap which, in combination with UV light, causes burns on affected skin.

From 2002 to 2005 *H.mantegazzianum* was the target of a multidisciplinary European-wide project funded by the EU. The research undertaken addressed aspects of the taxonomy and the ecology of the plant and the investigation of its natural enemy complex in the native range (PYŠEK et al., 2007). An assessment of insects and fungal pathogens associated with giant hogweed in the Caucasus as potential classical biological control agents revealed that none of these organisms was sufficiently specific to the target weed to be considered for release in Europe (COCK & SEIER, 2007). However, some unanswered questions concerning the host specialization of one particular fungal pathogen, *Phloeospora heraclei*, and the potential existence of distinct strains or pathotypes of this pathogen specific to different *Heracleum* species remained at the end of the EU project (SEIER &, 2007) and this is to be elucidated under the current WFD programme.

Phloeospora heraclei is a common and damaging pathogen of *H. mantegazzianum* in the Caucasus but has never been recorded on this plant species in the introduced European range, despite also being known from the European native species *Heracleum sphondylium*. Additionally, infection of *H. sphondylium* with *P. heraclei* strains ex *H. mantegazzianum* collected in the Caucasus was not achieved under quarantine greenhouse conditions, although selected cultivars of parsnip (*Pastinaca sativa*) and coriander (*Coriandrum sativum*) were shown to be susceptible (SEIER & EVANS, 2007). *Phloeospora heraclei* is also a known pathogen of wild parsnip in Europe (ALLESCHER, 1903).

Studies are currently being conducted in the quarantine facilities at CABI E-UK to elucidate further whether the fungal species *P. heraclei* does comprise host specific strains adapted to *H. mantegazzianum*, *H. sphondylium* and *P. sativa*, respectively. Furthermore, additional strains of *P. heraclei* ex *H. manteganzzianum* collected in the Caucasus will be evaluated for their infectivity towards individual parsnip and coriander cultivars.

FLOATING FAIRY FERN

The fairy fern or floating water fern (*Azolla filiculoides*, Azollaceae) is an attractive aquatic plant with delicate fern-like foliage that originates in the Americas. It was first recorded in the UK in around 1840 and has been sold continually ever since as a popular garden aquatic.
Azolla is, however, one of the most invasive plants in the UK today. Classified as a “High Impact” aquatic alien species by the UK Technical Advisory Group on the WFD, it has a remarkable ability to multiply, with fronds that grow rapidly, elongating until fragments break off to form new plants. *Azolla* is capable of forming mats on the water's surface up to 30 cm thick, which during hot weather can double in area in just four or five days. *Azolla* has escaped from gardens into the wider environment, becoming a problem on ponds, lakes, rivers and canals throughout the UK, including areas of conservation importance.
Fragmentation of the fronds makes lasting control of *Azolla* by mechanical means virtually impossible. This is compounded by the annual production of millions of tiny spores, which are released in autumn and grow into new plants the following year.

There are no organisms native to the UK that feed specifically on *Azolla* and the imported plant has not brought with it the full suite of natural enemies that would keep it in check in its native range of the Americas. Research has shown, however, that a 2 mm long North American weevil, *Stenopelmus rufinasus*, is one of *Azolla*'s main natural enemies and has long been established in the UK, with a first record in 1921, most likely introduced as a stowaway on imported *Azolla*. This beetle species has been shown to feed only on *Azolla* species, with all mobile life stages causing damage to the plant. The weevil has already been used to control *Azolla* very successfully in South Africa, where after extensive host range testing and climatic matching, it was released as a biocontrol agent providing control of even the heaviest infestations, without the need for chemicals or further control measures.
The weevil has been present in the UK for such an extended period that it is classed by DEFRA as ordinarily resident. Despite the presence of the weevil throughout the UK, control of *Azolla* by natural weevil populations is not always timely or apparent, with weevil dispersal seemingly limited in the UK. Following increased calls for an effective form of *Azolla* control in the UK, CABI developed methods to overwinter and mass rear *S. rufinasus* early in the season, to be supplied on demand to landowners with *Azolla* infestations. CABI now has an established "*Azolla* Control" business supplying *S. rufinasus* weevils to landowners across the UK. Ongoing research is being undertaken to improve our understanding of the weevils' distribution, mobility, population development, survival requirements and potential as natural control agents in the UK.

CONCLUSION

Biological control of invasive weeds has been successfully used worldwide. It is a good alternative when mechanical and chemical controls are too costly, insufficient or unsuitable. This control method is efficient and sustainable under economic constraints. Its action in the long term is particularly valuable when invasions reach such a large scale that eradication is not possible anymore. Biological control has a high potential in the present European movement towards increasing restrictions in the use of chemical control and the requirements of the WFD.

As shown by the examples discussed, there is a high potential for the biological control of a number of the worst aquatic and riparian invasive weeds, which are common to many European countries. Progress in research and implementation is well underway with effective control available for *Azolla*, field trials undertaken in the UK for Japanese knotweed and a number of promising potential control agents having been identified for the other named weed species.

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