Top 20 environmental weeds for classical biological control in Europe: a review of opportunities, regulations and other barriers to adoption

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Summary

Classical biological control remains the only tool available for permanent ecological and economic management of invasive alien species that flourish through absence of their co-evolved natural enemies. As such, this approach is recognized as a key tool for alien species management by the Convention on Biological Diversity (CBD), the European and Mediterranean Plant Protection Organization (EPPO) and the European Strategy on Invasive Alien Species (ESIAS). Successful classical biological control programmes abound around the world, despite disproportionate attention being given to occasional and predictable non-target impacts. Despite more than 130 case histories in Europe against insect pests, no exotic classical biological control agent has been released in the EU against an alien invasive weed. This dearth has occurred in the face of increasing numbers of exotic invasive plants being imported and taking over National Parks, forests and amenity areas in this region, as well as a global increase in the use of classical biological control around the world. This paper reviews potential European weed targets for classical biological control from ecological and socioeconomic perspectives using the criteria of historical biological control success, taxonomic isolation from European native flora, likely availability of biological control agents, invasiveness outside Europe and value to primary industry and horticulture (potential for conflicts of interest). We also review why classical biological control of European exotic plants remains untested, considering problems of funding and public perception. Finally, we consider the regulatory framework that surrounds such biological control activities within constituent countries of the EU to suggest how this approach may be adopted in the future for managing invasive exotic weeds in Europe.

Keywords: plant pathogens, *Buddleja*, *Fallopia*, *Acacia*, *Azolla*, *Ailanthus*, *Impatiens*, *Rhododendron*, *Robinia*, *Senecio*.

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Introduction

Although the problems caused by invasive plant species have been recognized for many decades throughout much of the world (Holm *et al.*, 1979; Cronk & Fuller, 1995; Weber, 2003), invasive alien plants have only recently being recognized by society in Europe for their significant cost to human activity, health, property values, aesthetics of the countryside, and biodiversity conservation. At the same time chemical management options for weeds decline, as increasing numbers of pesticides are being deregistered and more land in Europe is set aside from intensive agriculture under the Common Agricultural Policy. While the economic costs of alien species are poorly known for Europe, aside from a review for Germany (Reinhardt *et al.*, 2003), at a

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worldwide scale alien plants make up more than a third of the economic costs of alien species (US$350 billion; Pimentel, 2002). It has been estimated that up to a third of the flora of some European countries is now composed of species not of European origin that have at least naturalized, up to a tenth that have established and around one in a hundred that are significant alien invasive species (Williamson, 1996). In the UK this includes 39 species (Williamson, 1996). In France, 60 species are now considered to be causing damage to ecosystems and a further 157 species are considered potentially invasive (Aboucaya, 2004; Muller, 2004); while in Germany about 50 of 400 alien plant species are having significant negative impacts with half of these species affecting biodiversity (Kowarik, 2003; F. Klingenstein, pers. comm.). These numbers will increase and climate change will make a significant additional contribution by favouring species from Mediterranean regions (Walther *et al.*, 2002).

European scientists working on biological invasions have long recognized the problems posed by, and the unique ecological and evolutionary conditions associated with, invasive alien species around the world (e.g. Elton, 1958). In the 1980s international collaborative research programmes were set up through both the Scientific Committee on Problems of the Environment (SCOPE; part of the International Council of Scientific Unions) and the OECD sponsored Cooperative Research Programme focussed on research into alien invasive species. SCOPE aimed to not only increase understanding of both the species and recipient environmental aspects associated with invasions, but also to set up a framework for their management. Over a 21-year period, SCOPE published 16 reports and books (reviewed in Williamson, 1996; Mooney *et al.*, 2005), eight of which include European geographic coverage. These publications focus on the status of such invasions and academic assessments of why such invasions occur, etc., but very little on management. Significant collaborative research on invasive species through the EU Framework Program from the late 1990s included EPIDEMIE (http://www.ceh.ac.uk/epidemie/), focusing on invasive alien plants on Mediterranean Islands, and 'Giant Alien', a smaller project on *Heracleum mantegazzeanum* Sommier & Levier under FP5. Both these projects had species management components, but effective management strategies to the invasive species studied have neither been the dominant focus nor forthcoming. Under the current FP6, two current networks are DAISIE (http://www.daisie.ceh.ac.uk/) and ALARM (http://www.alarmproject.net/alarm/), neither of which focus on management solutions for existing invasions.

As such, management-outcome driven invasive species research in Europe is lagging way behind other countries such as North America, Australia, New Zealand and South Africa, which have been actively managing invasive plants since the early 20th century. Why is this? One reason is that impacts of invasive species have been much less evident in Europe than in other countries (Manchester & Bullock, 2000). Not through lack of 'propagule pressure' (i.e. opportunities for such species to arrive and establish), however, as Europeans have been historically the most active at moving exotic plants around the world (Mack, 2001). Land management has also been much more intensive in Europe, compared with many less densely populated regions, and the late 20th century agrochemical revolution provided unprecedented short-term suppression solutions for weeds. This is now changing, with EU goals to reduce areas of production and reduce chemicals in the environment through sustainable production methods.

Significant parts of the European and Mediterranean flora may also have evolved under conditions of high human disturbance and agricultural activity. As there remain few, if any, European habitats that have not been significantly altered by man, so the alien invaders may have had less chance of being better adapted to these managed European ecosystems than the native flora (Cronk & Fuller, 1995). Indeed, some evidence suggests that the main costs of invasive alien plants in Europe are largely economic, through such plants being a nuisance to human activities, health and aesthetic values, rather than through suppression of native plant biodiversity or damage to native ecosystems (e.g. Manchester & Bullock, 2000). In contrast, North America, Australasia and South Africa with much more extensive agriculture and pristine natural environments have been suffering severe economic losses and significant environmental decay from invasive plants for over 100 years.

By trial and error over the last 200 years, classical biological control has, in these and other countries, slowly proved itself to be the only low risk and viable, if not always reliable, long-term ecological solution to such invasions and, therefore, the only means for permanent ecological and economic management of introduced invasive alien species. Classical biological control uses coevolved and specific antagonists of the weed from its native range, which are then screened for risks to any prospective non-target native or commercially important species. These antagonists are then released into the weed populations and effectiveness is dependent on the natural enemy naturally invading such populations and providing long-term control. The approach has a long pedigree compared with many other areas of pest management. In countries outside Europe that promote its use, classical biological control has become a strongly science-based, highly regulated and internationally recognized approach that can complement or even remove the need for contemporary agrochemical-based management options.

Despite being source countries for 381 releases of classical biological control agents for alien plants around the world (Julien & Griffiths, 1998), no classical biological agents have ever been released against alien invasive plants within the European Union (Shaw, 2003). Weed biological control research has been restricted to inundating indigenous crop weeds with indigenous natural enemies (Müller-Schärer & Scheepens, 1997). Classical biological control against exotic insect pests, if rather poorly regulated, is practiced in Europe. The BIOCAT database (Greathead & Greathead, 1992) lists 137 agent species that have comprised 276 releases since 1901. Now that the increasing impacts and costs of invasive alien plants are being recognized in Europe, particularly in National Parks, forests, amenity areas and on islands (e.g. Muller, 2004), it is appropriate to review the future relevance and application of classical biological control of weeds in Europe, alongside the associated necessary regulations.

In this paper, we review opportunities and constraints for the use of classical biological control against alien plants in Europe. We attempt to prioritize the top 20 widespread alien plants invading non-cropping ecosystems in Europe for their potential as targets for classical biological control from an ecological, social and economic perspective. Cropping weeds have been the subject of a previous review (Schroeder *et al*., 1993). We also discuss public perception and the legislative and regulatory framework within the EU and its constituent countries and how these constrain adoption of this approach in Europe (cf. Ghosheh, 2005).

Why are aliens so invasive?

Many plants both native and alien to Europe are already, or have the potential to cause economic or environmental problems in Europe. Invasive alien species, however, have been singled out worldwide as a high-risk group under the CBD. Alien plants have a greater tendency to predominate in lists of 'worst weeds' in both natural and agro-ecosystems, as they have a greater tendency to form suppressive monocultures and as such far outweigh native species as regards impacts (Pimentel, 2002). The ecological interactions between a colonizing species and the environment it successfully colonizes, the so called 'invasion criterion' (Crawley, 1997), does not fundamentally differ between alien and native species. However, alien species colonization and invasion are accompanied by novel ecological and evolutionary processes. Novel ecological interactions take place with competitors (Williamson, 1996), mutualisms (Richardson *et al*., 2000; Cesar, 2005) and antagonists (Evans & Ellison, 2003), or lack thereof (Keane & Crawley, 2003), within new environmental arenas of resource availability and disturbance. Opportunities for rapid post-invasion evolution, including genotype hybridization, within founder populations leading to novel genotypes and transgressive (extreme) phenotypes showing higher fitness in the novel environment, although hard to demonstrate, are also associated with the overriding success of alien invaders over ecologically similar native species (Williamson, 1996; Müller-Schärer *et al*., 2004).

Classical biological control of weeds: practise and performance

The recently characterized 'enemy-release hypothesis' encapsulates how escape from natural enemies can act to increase invasiveness in alien species (Keane & Crawley, 2003). Classical biological control is an internationally recognized ecological approach that exploits this to manage invasive alien species for the public good. Where effective, an ecological equilibrium is permanently restored through top-down suppression of invader populations by the highly specific natural enemies (biological control agents) transported from the native range of the invader into its exotic range. This is achieved either from resource-limited agents exploiting high-density invader populations, or from the agents themselves escaping their natural enemies and reducing the invader to levels where invader density provides a negative feedback on agent populations. Biological control, therefore, may be effective even if the target is not being regulated by its natural enemies in the native range. Effective agents do not require regular application, as they spread naturally through the invader populations. Classical biological control has a historically tarnished reputation largely due to early unscientific and uncontrolled releases of vertebrate predators to control pests (e.g. releasing cats to control rats on islands). Even when this led to success, these predators also decimated native species. More recent cases of insect biological control agents spreading beyond their intended targets (e.g. the spread of *Harmonia axyridis* Pallas across Europe; Roy *et al*., 2005), result from historically unregulated use of biological control against insect pests in Europe. Classical biological control of weeds now adopts a precautionary approach using the most specific antagonistic invertebrates and microorganisms against selected targets and follows best-practice scientific risk analysis and regulatory approval prior to release (Sheppard *et al*., 2003). When conducted as such, negative effects have proved almost entirely predictable (Pemberton, 2000).

Classical biological control has internationally recognized standards and procedures under the International Plant Protection Convention (IPPC, 2005), the Organization for Economic Co-operation and Development (OECD, 2004) and the European and Mediterranean Plant Protection Organization (EPPO, 1999, 2000). While these standards are advisory, they reflect accepted, co-ordinated and effective risk analysis and decision-making processes and regulations that exist in several countries and organizations around the world that have pioneered classical biological control of weeds (Sheppard *et al*., 2003).

Classical biological control of weeds has a good safety record and a respectable rate of success, despite some high profile criticism (Louda *et al*., 1997). Over 1000 releases of more than 350 biological control agent species have been made against more than 100 target alien plants around the world since the late 1800s (Julien & Griffiths, 1998). Ten released agents have been observed feeding on non-target species. However, this feeding, in all cases except one, was anticipated by the pre-release risk assessment, using internationally recognized host specificity testing procedures (Pemberton, 2000; Sheppard *et al*., 2005). This non-target feeding is therefore a consequence of the government decision to release the agent, based on societal values at that time, and not weaknesses in the risk assessment process. Of all agents released, only two cases (0.6%) have led to anticipated feeding that caused significant non-target population suppression in one or two of the countries where such agents were released (Louda *et al*., 2003). In terms of success, biological control of weeds is often disparaged as only 20% of agent releases (Crawley, 1989) and 34% of agent species released (Julien *et al*., 1984) have significantly suppressed their target weeds. However, from a target perspective, a review of completed programmes in Australia, South Africa, New Zealand, Hawaii and Mauritius by Myers and Bazely (2003) shows that more than 75% (range 50–85%) of target weeds have been significantly or permanently controlled. Chance of control success is not particularly constrained by target life-history strategy or genetic variability (Chaboudez & Sheppard, 1995), climate or continent (Julien *et al*., 1984), but is often related to the amount of investment in the programme (Fowler, 2000).

Targets for classical biological control of weeds: prioritizing invasive plants in Europe

For this review, the available scientific literature listing and for prioritizing alien plant species (mostly for rate of spread, distribution and perceived economic impacts) across European countries (Holm *et al*., 1979; Crawley, 1987; Clement & Foster, 1994; Lowe *et al*., 2000; Weber, 2003; Aboucaya, 2004; CABI, 2004; Muller, 2004; EPPO, 2005; Brunel & Tison, 2006) was cross-referenced. This generated a full list of over 200 of what we accepted to be the most important alien invasive species in both Mediterranean and temperate climates across terrestrial and aquatic ecosystems. In Europe, where weed biological control is still in its infancy, it will be important to identify initial weed targets that will have the widest ownership and be acceptable to even the sternest critics of biological control (Lonsdale *et al*., 2001). With this in mind, the list was then assessed for biological control potential based on (i) historical success of biocontrol against these targets, ecological homologues and related species, (ii) taxonomic isolation of these weeds from European native flora (as a measure of risk of non-target damage), (iii) likelihood of suitable natural enemies being available as potential agents, (iv) target value to agriculture, horticulture and forestry (potential conflicts of interest) and (v) whether species were significantly invasive outside Europe (opportunities for international collaboration; see Sforza & Sheppard, 2006). Impacts on European biodiversity could not be used, as so little data are available, but are presented where known. Each author independently considered these five questions and the number of positive responses was tallied for each species across all authors and used to prioritize the weeds for biological control. Where the number of positive responses was the same for different species, the relative geographical distribution and local abundance within and between European countries was used to further prioritize the species. It was not possible to leave out all species with actual or potential conflicts of interest, because in a continent as culturally diverse as Europe nearly all alien species are valued by someone.

Twenty alien plant species were identified through this process as having positive responses to four of five of the questions posed. These are listed in Table 1.

Of the remaining species prioritized, a further five species had three positive responses to the five questions and were considered to be sufficiently suitable to merit a mention but are not discussed further here. These were: *Cortaderia selloana* (Schultes & Schultes fil.), *Eucalyptus globulus* Labill., *Lagarosiphon major* Ridley Moss., *Opuntia* spp. (e.g. *O. ficus-indica* (L.) Mill and *O. monoacantha* (Willd.) Haw) and *Ricinus communis* L.

Of the 20 potential targets for classical biological control in Table 1, five have had substantially or partially successful (*sensu* McFadyen, 1998) biological control programmes implemented against them elsewhere in the world: *Acacia* spp., *Azolla filiculoides* Lam. and *Solanum elaeagnifolium* Cav. (in South Africa),

Table 1 Exotic invasive plants in Western Europe prioritized as potential biocontrol targets arranged by lines into groups of decreasing priority, but of similar priority within each group

Species	Life form*	Area of origin	EU climate distribution	Genus native to Europe	Conflict of interest†	Past or current biological control programs/ publications
Buddleja davidii	Ph	China	Temperate	No‡	O	Yes
Fallopia japonica	Ge	Japan	Temperate	Yes	No	Yes
Acacia dealbata	Ph	Australia	Mediterranean	No‡	O	Yes§
Azolla filiculoides	Hy	N America	Temp/Med	No‡	No	Yes§
Ailanthus altissima	Ph	China	Temp/Med	No‡	No	Yes
Impatiens glandulifera	He	India	Temperate	Yes	O	No
Rhododendron ponticum	Ph	S Europe	Temp/Med	Yes	O	Yes
Robinia pseudoacacia	Ph	N America	Temperate	No	F	No
Senecio inaequidens	He	S Africa	Temp/Med	Yes	No	Yes
Ambrosia artemisiifolia	Th	C America	Temp/Med	Yes	No	Yes§
Carpobrotus edulis	Ch	S Africa	Temp/Med	No‡	No	No
Heracleum mantegazzianum	He	W Asia	Temperate	Yes	No	Yes
Solanum elaeagnifolium	He	S America	Tem/Med	Yes	No	Yes§
Baccharis halimifolia	Ph	N America	Mediterranean	No	No	Yes§
Hydrocotyle ranunculoides	Hy	N America	Temp/Med	Yes	No	Yes
Ludwigia grandiflora	He	S America	Temp/Med	Yes	No	Yes
Crassula helmsii	Hy	Australasia	Temperate	Yes	No	No
Elodea canadensis	Hy	N America	Temperate	No	No	No
Myriophyllum aquaticum	Hy	S America	Temp/Med	Yes	No	Yes
Solidago canadensis	Ge	N America	Temperate	Yes	No	No

*Ph = Phanerophyte, Ge = geophyte, Hy = hydrophyte, He = hemicryptophyte, Th = therophyte, Ch = chamaephyte.
†O = current ornamental interest, F = value as forestry tree – simple aesthetic value of certain aliens weeds is not considered a conflict of interest as biocontrol will only reduce their density not eradicate them.
‡Family or subfamily also not native to Europe.
§Has had a biological control program somewhere that has recorded at least partial success (*sensu* McFadyen, 1998)

Baccharis halimifolia L.(in Australia) and *Ambrosia artemisiifolia* L. (in Russia). Six are aquatic weeds for which, as a group, biological control has had a particularly high success rate worldwide (Forno & Julien, 2000). Six have potential classical biological control agents already present in Europe that are either native European species (for *Rhododendron ponticum* L. and *Senecio inaequidens* DC.) or accidentally introduced exotic species (for *S. inaequidens*, *Robinia pseudoacacia* L., *A. filiculoides* and *A. artemisiifolia*). Eight have highly similar congeners also invading Europe (see species accounts), and in some of these cases such congeners might be better considered as biological control targets together to avoid future species replacement if their habitats and ranges overlap. Nine are in genera not native to Europe and five of these are in families or subfamilies with similar status. This should lower the likelihood that specialist agents might attack native non-target species and allow broader levels of specificity in potential agents selected against such targets (assuming there is a low risk of such agents finding related natives in neighbouring Asia and Africa).

Top 20 potential targets for classical biological control of weeds in Europe

Each of the 20 species in Table 1 is described in the following species accounts, providing information relevant to their potential as targets for classical biological control. These species accounts draw on, but do not individually cite standard references as follows: Mabberley (1987) for species numbers and geographical distribution per genus; Randall (2002) for known weeds; regional weed importance from Crawley (1987) and Clement and Foster (1994) for the UK, Muller (2004) for France, Kowarik (2003) for Germany and Eastern Europe, Brunel and Tison (2006) and EPIDEMIE (http://www.ceh.ac.uk/epidemie and associated publications) for Mediterranean countries and islands and Flora Europaea (Tutin *et al*., 1964–1991) for Europe in general; and biological control releases from Julien and Griffiths (1998). Significant conflicts of interest for control of these weeds are also highlighted, where appropriate; however here we do not consider 'some aesthetic value' as a significant conflict of interest for biological control of these weeds, as biological control causes only weed density reduction at high density rather than eradication (cf. Table 1).

Buddleja davidii *Franchet*

Buddleja (Buddlejaceae) contains *c.* 100 species originating from eastern Asia of which 15 species are considered weeds worldwide. Buddlejaceae is exotic to Europe. *Buddleja davidii* is the dominant invasive species in Europe, however six other species are also naturalized (*B. albiflora* Hemsley, *B. alternifolia* Maxim., *B. globosa* Hope, *B. japonica* Hemsley, *B. lindleyana* Fortune ex Lindley and a *B. davidii* × *B. globosa* hybrid (*B.* × *weyeriana* Weyer). *Buddleja* spp. are popular ornamentals. *Buddleja davidii* is also valued as a butterfly attractant and a secondary succession revegetation species on scree slopes and mining sites.

Origin, life history and ecology

Buddleja davidii is a shrub to small tree (phanerophyte) native to the highlands of south-western China (from Tibet to Hubei), where it is restricted to mineral soils and scree slopes, forms low thickets (1–1.5 m high) and extends up to 2600 m a.s.l. Reproduction is entirely by small windborne seeds (*c.* 3 million per plant; Miller, 1984) and plants have an extensive root system which assists drought tolerance and grows well in soils with pH 5.5–8.5.

Distribution and importance

Buddleja davidii is a cosmopolitan invader in temperate regions (e.g. forestry weed in Australasia) with a European distribution from the Mediterranean to Bergen in Norway. Introduced to Europe as an ornamental in the 1890s, it spread rapidly from the 1930s. Currently most abundant in Western Europe, it is in the top 20 invasive alien plants in the UK and France and common in other European cities. Habitats include rock faces, walls, stream-sides, along railway lines and on disturbed urban sites. It can displace brickwork, paving, etc., often in inaccessible places, leaving high control and repair costs. Infestations form monocultures 2–5 m in height and fruit in the first season, with individuals living up to 40 years (Esler, 1988). Regeneration from cut stumps and seedbanks waiting for disturbance complicate management.

Existing and potential biological control

Two weevils, *Cleopus japonicus* Wingelmüller and *Mecyslobus erro* Pascoe have been imported from China into New Zealand quarantine. The leaf-feeding *C. japonicus* (Fig. 1A and B), has been shown to significantly reduce plant size and performance, even killing 1 m tall plants (Kay & Smale, 1990; Zhang *et al.*, 1993). The completed risk assessment of *C. japonicus* has led to a decision to release it as a classical biological control agent (N. Kay, pers. comm.). Two pathogens have also been reported as quite specific to *B. davidii*; *Pseudocercospora buddleiae* (W. Yamam.) Goh & W.H. Hsieh and *Septoria merrillii* Syd. In the UK stump treatments based on native fungal pathogens are being considered to tackle regrowth (Evans, 2002).

Fallopia japonica *(Houtt.) Ronse Decraine*

Fallopia (Polygonaceae) contains *c.* 24 species worldwide of which seven are considered weeds. *Fallopia japonica* var. *japonica* (Houtt.) Ronse Decr., the most invasive clone (Bailey, 1994), is referred to as *Reynoutria japonica* Houtt. in some parts of Europe and *Polygonum cuspidatum* Sieb. & Zucc. in Japan and North America. *Fallopia japonica* var. *compacta* (Houtt.) Ronse Decr. (Hook. f.) J.P.Bailey, two other species: *F. sachalinensis* and *Fallopia baldschuanica* (Regel) Holub, and a *F. japonica* × *F. sachalinensis* (Schmidt) Ronse Decraine hybrid (*F.* × *bohemica* Chrtek & Chrtkova) J.Bailey) are also invasive, although their relative importance in Europe is still being studied. The hybrid appears to spread faster than either parent (Mandák *et al.*, 2004).

Origin, life history and ecology

Fallopia japonica is rhizomatous dioecious perennial (geophyte) native to Japan, Korea and Taiwan where it grows in sunny places on hills, high mountains, road verges and ditches, river gravels and managed pastures on a wide range of soils from sea level to 2400 m a.s.l. (Maruta, 1983; Child & Wade, 2000). Reproduction is mainly vegetative from the rhizome fragments, but outcrossed wind-borne seed may also be important.

Distribution and importance

Fallopia japonica was introduced into Europe as an ornamental in the 1820s and spread exponentially throughout Europe during the 1900s on disturbed areas, roadsides and river banks via accidental transport of rhizome fragments. European material, of at least var. *japonica*, remains one female clone and produces no viable seed. These *Fallopia* spp. are invasive throughout the temperate world including much of North America and more recently in Australasia. They are on the IUCN 100 worst invasive species list (Lowe *et al.*, 2000), are the second most damaging alien plant in Germany (landholder poll) and are in the top 10 invasive plant species in France and the UK, where *F. japonica* var. *japonica* is one of three species having impacts on biodiversity (Manchester & Bullock, 2000). *Fallopia* spp. increase risks of flooding, and the deep rhizomes hinder construction projects and cause physical damage to

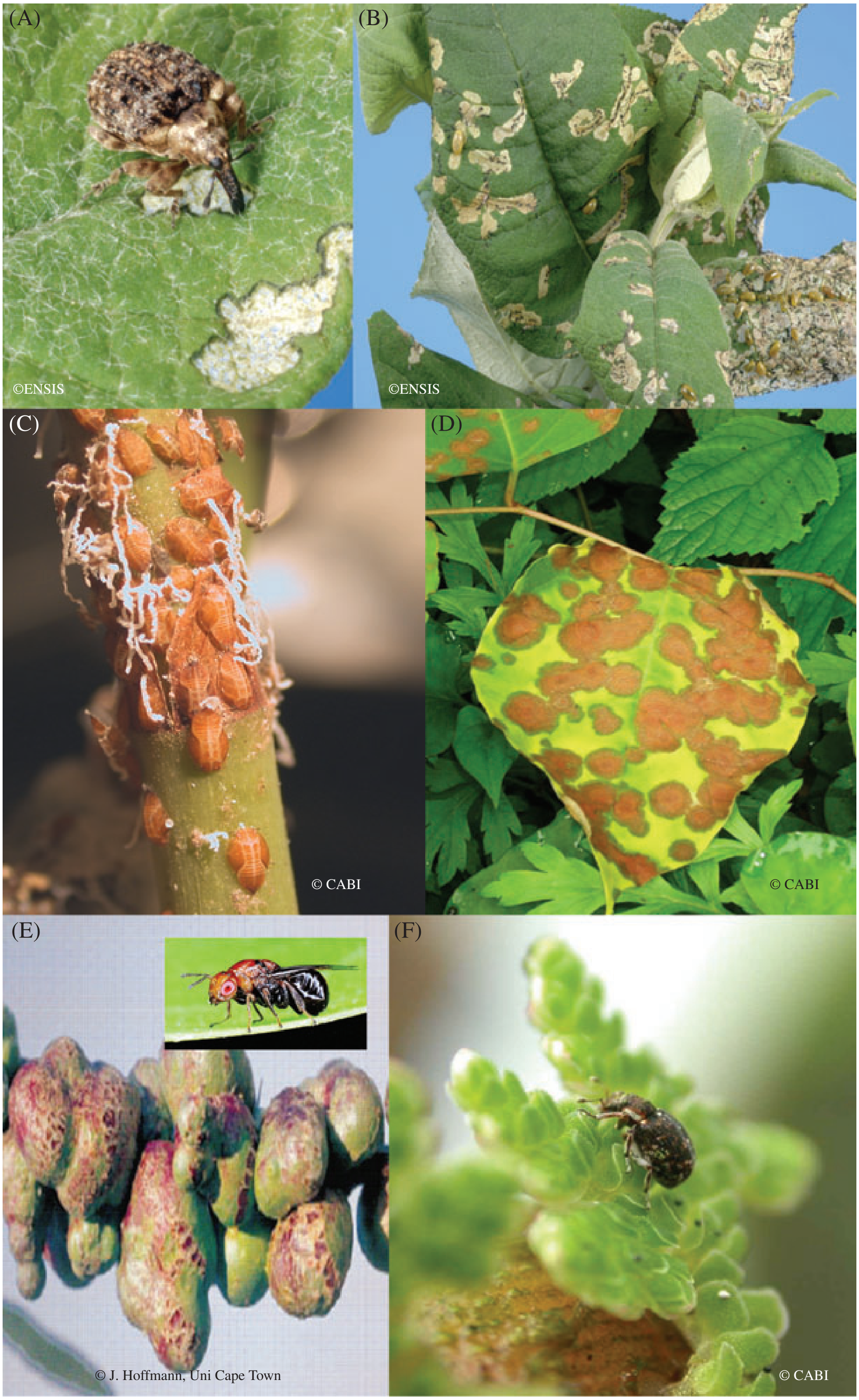

Fig. 1 Potential biological control agents for alien invasive plants in Europe: (A) the weevil and (B) the larvae of the weevil, *Cleopus japonicus* on *Buddleja davidii*, (C) the psyllid *Aphalara* sp. and (D) leaf spot *Mycosphaerella* sp. on *Fallopia japonica*, (E) the gall wasp *Trichilogaster acaciaelongifoliae* on *Acacia longifolia*, (F) the weevil *Stenopelmus rufinasus* on *Azolla filiculoides* (see text for details).

drainage structures, building foundations and road surfaces (Beerling, 1991). Potential UK control costs there have been estimated at 2.25 € billion (£1.56 billion, DEFRA, 2003).

Existing and potential biological control

Biological control is now recognized as the only long-term, sustainable solution to *Fallopia* spp. (Shaw & Seiger, 2002), but a full programme has been a long time coming. Since 2003, a predominantly UK consortium run through CABI has conducted field surveys in Japan, where the plant is heavily damaged compared with the exotic range. Selected insects and fungal pathogens are undergoing host range screening including a weevil (*Lixus* sp.), a psyllid (*Aphalara* sp.) (Fig. 1C), a rust (currently identified as *Puccinia polygoni amphibii* var. *tovariae* Arthur) and a leaf-spot disease (*Mycosphaerella* sp.) (Fig. 1D).

Acacia dealbata *Link*

Acacia (Mimosoideae, Fabaceae) contains *c.* 1200 species from Australia and other tropical and warm parts of the world of which 320 are considered weeds worldwide. The subfamily Mimosoideae is exotic to Europe. *Acacia dealbata* is one of 10 invasive or naturalized *Acacia* species in southern Europe of Australian origin (*A. saligna* (Labill.) Wendl, *A. melanoxylon* R. Br., *A. longifolia* (Andrews) Willd., *A. retinodes* Schldl., *A. cyclops* G. Don, *A. mearnsii* De Wild., *A. baileyana* F. Müller, *A. decurrens* Willd., *A. pycnantha* Benth., *A. sophorae* (Labill.) R. Br., *A. verticillata* (L'Her.)Willd.) one from South Africa (*A. karoo* Hayne), and one neotropical species (*A. farnesiana* (L.)Willd.). *Acacia* spp. are valued for their early spring yellow flowers (flower trade and apiculture), quality timber (some species) and for providing rapid cover in open dry areas in North Africa.

Origin, life history and ecology

Acacia spp. are nitrogen-fixing shrubs to small trees (phanerophytes). *Acacia dealbata* is a typical Australian *Acacia* sp. in Europe. Native to south-eastern Australia, where it is a widespread species in dry sclerophyll forests on slopes and stream banks on acid soils, it grows up to 15+ m, reproduces entirely by seed and quickly resprouts following cutting, fire or frost (including from the roots). Hybridization and grafting in Europe allow survival on more calcareous soils.

Distribution and importance

Introduced to Europe as an ornamental in the 1790s, it invaded southern France by the 1860s. *Acacia dealbata* has naturalized and become invasive in Mediterranean climates from Portugal to Italy and often in association with other Australian *Acacia* spp. *Acacia* spp. are in the top 10 invasive alien plants in Portugal and the Mediterranean islands and in the top 30 in Spain and France. *Acacia mearnsii* is on the IUCN list of the world's 100 worst alien invasive species (Lowe *et al.*, 2000). *Acacia* spp. invade maquis vegetation in the Mediterranean and dune systems, with or without forestry, along the Atlantic coast of Spain and Portugal as well as along motorway verges and waste places in and around towns. Dense monocultures prevent germination of native species under the canopy (C. Werner, pers. comm.). Resprouting from cut stumps and the high seedbank impede control efforts.

Existing and potential biological control

In South Africa, where the timber is economically important, biological control programmes have targeted seed production with gall wasps, weevils and a gall-forming rust fungus from Australia (Table 2) and found no non-target impacts (Dennill *et al.*, 1999; Morris, 1999). Spread of *A. saligna* and *A. longifolia* was successfully managed, while results for *A. pycnantha*, *A. melanoxylon* and *A. cyclops* also look promising and a programme against *A. dealbata* has been initiated. Portugal is already taking advantage of this South African expertise and approving the importation of its first weed biological control agent against *A. longifolia* into quarantine for further risk assessment (Fig. 1E; H. Marchante, pers. comm.).

Ailanthus altissima *(Miller) Swingle*

Ailanthus (Simaroubaceae) contains 10 species confined to Asia and Australia of which *A. altissima* (from temperate and subtropical China), the only member of the family in Europe, is considered an invasive species in most temperate regions of the world.

Origin, life history and ecology

This medium to large frost tolerant, shade intolerant early successional dioecious tree (phanerophyte) grows from temperate to subtropical and humid to semi-arid climates. It is widely distributed in its Chinese native range. It can grow to 30 m at a rate of 1.5 m a year on any well drained soil, produces up to 300 000 seeds a year and sprouts readily from root cuttings (Muller, 2004).

Distribution and importance

Female *A. altissima* trees were introduced into Italy and the UK in the late 1700s, primarily as street trees (males have a disagreeable odour) and to support silk production. *Ailanthus altissima* spread extensively in the next 200 years. Listed as a top 20 weed on Mediterranean islands, *A. altissima* is mainly distributed around the

Table 2 Natural enemies of Australian *Acacia* spp. considered as biocontrol agents in South Africa (Dennill *et al.*, 1999; Morris, 1999; Hill *et al.*, 2000, S. Neser, pers. comm.)

Natural enemies	Stage attacked	Host range	Date first used (damage)
Weevils			
Melanterius sp. (near *maculatus*)	Seeds	*A. dealbata*	1994 (?)
Melanterius maculatus Lea	Seeds	*A. mearnsii, A. decurrens*	1994 (?), 2001 (?)
Melanterius ventralis Lea	Seeds	*A. longifolia*	1985 (extensive)
Melanterius servulus Lea (type A)	Seeds	*A. cyclops*	1991 (considerable)
Melanterius acaciae Lea	Seeds	*A. melanoxylon*	1986 (extensive)
Melanterius compactus Lea	Seeds	*A. saligna*	2001 (?)
Wasps			
Bruchophagus acaciae (Cameron)	Seeds	*Acacia* sp.	Not released
Trichilogaster acaciaelongifoliae Froggatt	Bud gall	*A. longifolia*	1982 (extensive)
Trichilogaster signiventris Girault	Bud gall	*A. pycnantha*	1987 (extensive)
Trichilogaster trilineata (Cameron)	Shoot/flower	*A. mearnsi, A. dealbata, A. baileyana*	Not released
Flies			
Dasineura dielsi	Pod gall	*A. cyclops*	2002 (?)
Pathogens			
Uromycladium tepperianum (Sacc.) McAlp.	Gall rust	*A. saligna*	1987 (extensive)
Cylindrobasidium laeve (Pers.:Fr.) Chamuris	Stump	*A. mearnsii, A. pycnantha*	Mycoherbicide

Mediterranean coasts of Eurasian countries where it can suppress many native species through allelopathy (Heisey, 1996). *Ailanthus altissima* roots cause significant structural damage and exposure to the sap through cuts and abrasions in the skin can cause cardiac problems (Bisognano *et al.*, 2005).

Existing and potential biological control

Surveys conducted in China by USDA Forest Service identified nine specific plant pathogens and four arthropods (Zheng *et al.*, 2004). Of these, two weevils [*Eucryptorrhynchus brandti* (Harold) and *Eucryptorrhynchus chinensis* (Olivier)], one heteropteran (*Orthopagus lunulifer* Uhler), three fungal pathogens (*Alternaria ailanthi* Zhang & Guo, *Aecidium ailanthi* Zhuang and a *Coleosporium* sp.) have been selected for further study which could be through collaboration with Europe. A commercial stump treatment product (Stumpout^{TM}) based on the fungus *Cylindrobasidium laeve* (Pers.) Chamuris is used in South Africa killing 80% of treated stumps (Lennox *et al.*, 1999).

Azolla filiculoides *Lam.*

Azolla contains eight species from Mediterranean to tropical climates all of which are considered as weeds in introduced regions. Only *A. filiculoides* and *A. mexicana* C. Presl., both from temperate and tropical America, occur in Europe. *Azolla* is the only genus in the Azollaceae, a family exotic to Europe.

Origin, life history and ecology

Azolla filiculoides is a small annual floating fern (hydrotherophyte) that reproduces both vegetatively and by sexual spores. Fragmentation and regeneration are the most likely cause of the explosive spread of this weed (Sculthorpe, 1967) helped by human movement.

Distribution and importance

Following escape from aquaria and botanical gardens in the mid 19th century, *A. filiculoides* became naturalized in slow moving and still water in ponds, canals, dykes and lakes, where it forms dense mats turning red in the autumn. The plant is now almost cosmopolitan in West-Central Europe, South Africa, China and Australasia. As a nitrogen fixer it can persist on infertile water bodies and is valued elsewhere as a fertilizer in rice production, as well as for mosquito control (Hu *et al.*, 1989). However, unmanaged floating mats cut out light and create anaerobic conditions unfavourable to existing biodiversity, while affecting water body recognition and recreational fishing. Post-control regeneration can take place if spore production has occurred.

Existing and potential biological control

In South Africa, releases of a frond-feeding weevil, *Stenopelmus rufinasus* Gyllenhal from Florida (Fig. 1F) as a classical biological control agent, have resulted in complete control at all sites and local extinction of red waterfern at 43% of the 46 release sites so far (Hill, 1999). Introduced accidentally and probably repeatedly in the UK, Belgium and Italy since the 1920s, this weevil has been less effective in the colder European regions. In the UK, *S. rufinasus* is being redistributed and innundatively applied early in the season (this is acceptable given its 'ordinarily resident' status) to prevent and control *Azolla* outbreaks (Shaw *et al.*, 2004). This weevil has greater potential in southern Europe, if it has not already arrived, and could be released either through between-country movement or as a classical biocontrol agent following a recognized risk assessment. A flea beetle, *Pseudolampsis guttata* (LeConte), has also undergone risk assessment in South Africa and shown to be restricted to the Azollaceae (Hill & Oberholzer, 2002). While South Africa chose not to release it (considered a threat to native *Azolla* spp.), there is no such impediment in Europe.

Impatiens glandulifera *Royle*

Impatiens (Balsaminaceae) contains *c.* 850 species from the North Temperate and Tropical regions (one from Europe) of which 17 are considered weeds worldwide. *Impatiens glandulifera* is currently the dominant invasive in the genus in Europe. However, four other exotic species are naturalized (*I. capensis* Meerb, *I. parviflora* DC., *I. balfourii* Hooker, and *I. balsamina* L.).

Origin, life history and ecology

Impatiens glandulifera is from the western Himalayas between 2000 and 2500 m a.s.l., where it is not a weed. Like its congeners, *I. glandulifera* is an annual seed plant (therophytes) that grows in riparian zones along rivers on wet and nutrient-rich alluvial soils and in wet woodland. Its range may be limited by cold climates. Up to 2500 seeds are produced per plant, following either insect or self pollination, and projected 3–5 m from the parent by explosive fruits (Willis & Hulme, 2002). Dispersal is by submerged seeds in water currents, but the seedbank is not long-lived.

Distribution and importance

Impatiens glandulifera was introduced as an ornamental first into England in the 1830s, but gained a strong interest amongst beekeepers. Exponential spread has occurred in the last 50 years down river systems and by human spread. *Impatiens glandulifera* is now widespread along Europe's river systems in 23 European countries. It is the third most important alien plant in Germany (landholder poll), a top 20 weed in the UK and France and invasive in 12 other EU countries (CABI, 2004). The weed hinders storm water drainage in summer and its dieback in winter contributes to the erosion of riverbanks. Monocultures along rivers diminish native species adapted to such habitats, including the native *Impatiens noli-tangere* L. (Daumann, 1967). *Impatiens glandulifera* is thought to have a detrimental effect on native plant species through competition for space and nutrients and an ability to monopolize pollinators (Chittka & Schürkens, 2001).

Existing and potential biological control

Only a literature search has been carried out on the native natural enemies of *I. glandulifera* and its congeners (Fowler & Holden, 1994), although samples from international herbaria show evidence of significant damage in the native range (R. Tanner, pers. comm.). The one native species in the Balsaminaceae, *I. noli-tangere*, supports a protected moth in the UK (Hatcher & Alexander, 1994), so potential biological control agents would have to be specific to *I. glandulifera*. An exotic rust, *Puccinia komarowii* Tranzsch, from the native range of *I. parviflora*, and highly specific to it, has spread across Europe. It causes high mortality and has potential as a biological control agent (Eliás, 1995; P. Eliás, pers. comm.). Similar agents may exist for *I. glandulifera*.

Rhododendron ponticum *L.*

Rhododendron (Ericaceae) contains *c.* 850 species worldwide of which 84 are considered to be weeds. *Rhododendron ponticum* is invasive in the UK and France and naturalized in Belgium and Germany, although, along with three other *Rhododendron* spp. it is native to southern Europe. Two other exotic *Rhododendron* spp. have naturalized in Europe; *R. lutem* Sweet (Asian species in Eastern Europe) and *R. lapponicum* (L.) Wahlenb. (USA species in Scandinavia). The horticultural value of the genus *Rhododendron* presents a significant conflict of interest.

Origin, life history and ecology

Invasive *R. ponticum* in the UK is considered to be a *R. ponticum* subsp. *baeticum* (Boiss. & Reuter) Hand.-Mazz × *R. catawbiense* Michaux (US native) hybrid of horticultural origin, as it is unlikely the pure *R. ponticum* subsp. *baeticum* originally introduced from Portugal in the late 1700s (Milne & Abbott, 2000) could survive the harsh winter of 1895 (Milne, 2004). *Rhododendron ponticum* is an erect evergreen shrub 2–4 m (phanerophyte) which grows best on sandy well-drained acidic podsols, but can occur on wet clay, brown earths, alluvium and peat. Mycorrhizae assist on nutrient poor soils and allelopathy may also aid invasion (Rotherham, 2003). Reproduction is by seed; more than a million small, very light wind-borne seeds are produced per plant per year. *Rhododendron ponticum* subsp. *baeticum* is now endangered in its native range (Mejías *et al.*, 2002).

Distribution and importance

Rhododendron ponticum has spread from a naturalized, prized garden plant to an invasive category 4 species (Cronk & Fuller, 1995) and is high up in the top 20 invasive plants in the UK, due in part to the threat it is posing to an endangered plant species [*Coincya wrightii* (OESchulz)] (Manchester & Bullock, 2000). It costs 3500 € ha^{-1} (D. Burton, pers. comm.) in clearance costs, because re-treatment of vigorous regrowth is required. *Rhododendron ponticum* is also an increasingly important host for the 'sudden oak death' pathogen *Phytophthora ramorum* S. Werres, A.W.A.M. de Cock (Werres *et al.*, 2001) and the recently identified *P. kernoviae* (DEFRA, 2004).

Existing and potential biological control

Conflicts of interest that surround *R. ponticum* would probably mean that a fungal stump treatment based on native plant pathogens, possibly using *Chondrostereum purpureum* (Pers.) Pouzar, would be the favoured biological control choice (Evans, 2002). Early seed collectors of *Rhododendron* spp. referred them being full of 'hungry grubs' (J. Cross, per. comm.), so a classical biological control strategy aimed at seeds and preventing spread may also be possible.

Robinia pseudoacacia *L.*

Robinia (Fabaceae) contains four species from North and Central America, all of which are considered as weeds worldwide. *Robinia pseudoacacia* is valued for its showy fragrant flowers and fast growing strong rot-resistant wood (good for fence posts, and firewood). Its control will present conflicts of interest based on these qualities. *Robinia hispida* L. is also locally naturalized in southern France.

Origin, life history and ecology

Native to the humid regions of the Eastern US, *R. pseudoacacia* is a 10- to 25-m tall, early successional leguminous tree (phanerophyte) that spreads rapidly by both vegetative and sexual reproduction. Suckering and nitrogen-fixing root nodules assist in its rapid establishment and spread.

Distribution and importance

Robinia pseudoacacia, introduced in the 1700s as an ornamental into southern and central Europe, has undergone widespread planting for shelterbelts and land reclamation and is now extremely widespread south of Scandinavia. It is also invasive in all other temperate regions of the world except South Africa. Its rapid spread creates monocultures that displace native species, reduce the forest canopy composition diversity and prevent shade tolerant native species regaining dominance (Pacyniak, 1981; Kowarik, 1990) Its seeds, leaves, and bark are also toxic to humans and livestock (Hickman, 1993).

Existing and potential biological control

Three North American insects have already established on *R. pseudoacacia* in Europe. The gracillariid leaf-mining moth, *Phyllonorycter robiniella* (Clem.), is found from Switzerland (since 1983) to Poland and Germany to Italy, whilst the cecidomyiid gall midge, *Obolodiplosis robiniae* (Haldeman) from the eastern USA, is now found in Italy, Slovenia and in the Czech Republic along with the widely distributed locust borer *Megacyllene robiniae* (Forster) (Cerambycidae). *Phyllonorycter robiniella* causes premature leaf drop that negatively influences tree appearance and as such has itself been the target of a biological control program in Italy (Wojciechowicz-Żytko & Jankowska, 2005). Relatively high infestations of *O. robiniae* also cause leaf fall, but the tree soon produces regrowth (Duso *et al.*, 2005). *Megacyllene robiniae* tunnels serve as entry points for the fungus *Phellinus rimosus* (Berk.) Pilát (syn. *Fomes rimosus* (Berk.) Cooke), which causes extensive wood decay and root rot (Hoffard, 1992). Augmenting these species in Europe could provide one biocontrol strategy, but *R. pseudoacacia* also has other natural enemies in its native range that could be targeted at less desirable parts of the plant, e.g. the seeds.

Senecio inaequidens *DC.*

Senecio (Asteraceae) contains *c.* 1500 species worldwide of which 133 are considered weeds. *Senecio inaequidens* is the dominant invasive species throughout western Europe, however five other South African species are also naturalized and becoming invasive [*S. angulatus* L.f (N Italy & S. Spain), *S. deltoideus* Less., *S. mikanioides* Otto (S&W EU), *S. pterophorus* DC. (UK E), *S. elegans* L. (SW Eu), *S. grandiflorus* L.f., (UK)] together with *S. smithii* DC. (UK), from S. America and *S. ovatus* (P.Gaertner, Meyer & Scherb.) Willd. from Asia.

Origin, life history and ecology

Senecio inaequidens is a tussock-forming herbaceous perennial (chamaephyte) of waysides, grassland and pasture native to coastal ranges of South Africa. The plant lives 5–10 years, starts to flower within a few months, has a 6-month flowering period, and produces up to 10 000 fertilized seed per plant. Seeds are dispersed by wind, water and can attach to grazing animals and form a seedbank that lasts at least 2 years (López-García & Maillet, 2005).

Distribution and importance

Senecio inaequidens was introduced as a wool contaminant and grows well in temperate to Mediterranean climates on most soil types up to 2500 m a s l. Significant invasions spread from original entry points in southern Germany (1889), Belgium (1892), UK (1928), France (1936), Holland (1939) and Italy (1947) into suitable habitats in each region within 40 years. It infests coastal habitats, fallow land, pastures (causing alkaloid toxicity to livestock and decreasing land values), invades natural grasslands in National Parks and is a major weed of perennial crops. It also threatens several rare native species. Cultural, grazing and chemical management of the weed have met with poor success (Muller, 2004).

Existing and potential biological control

Senecio inaequidens is one of a group of related species that invade pastures throughout the world. Although a few visits to South Africa have found potential biological control agents for Australia and Hawaii (M. Ramadan, pers. comm.), a full assessment remains to be completed. Classical biocontrol agents would require very high specificity, given the number of European native *Senecio* spp. Two antagonists in Europe already significantly damage the plant. A rust of Australian origin, *Puccinia lagenophorae* Cooke that is now quite cosmopolitan can kill susceptible genotypes in Europe, although resistance is present in many populations, while the ragwort aphid, *Aphis jacobaeae* Schrank, infests the flowering shoots much more heavily than those of its normal host reducing seed set (Fort *et al*., 2004).

Ambrosia artemisiifolia *L.*

Ambrosia (Asteraceae) consists of 21 species (one native to Europe) worldwide of which all are considered weeds. *Ambrosia artemisiifolia* from North America is the most widespread invasive species in the genus. However, three other species of North American origin are increasingly widespread in Europe: *A. coronopifolia* Torrey & A. Gray, *A. trifida* L. and *A. tenuifolia* Sprengel.

Origin, life history and ecology

Ambrosia artemisiifolia is a summer annual herbaceous seed plant (therophyte) 20–150 cm high and native to North America. Seedling emergence is from May to July, while flowering spikes appear from mid summer to mid autumn or the first frosts. The plant grows in profusion along roadsides, waste places and river systems.

Distribution and importance

Introduced into Germany in 1863 and France 2 years later, it spread rapidly via the Rhone valley into Belgium and the Netherlands, reaching the UK and eastwards into Hungary, the Balkans and Ukraine. The largest infestations are in the Rhone valley, Northern Italy and the Carpathian basin. Although it is a significant weed in sunflower crops, its major threat, together with *A. trifida*, is its allergenic pollen produced in late summer and autumn. As such, this is the most costly alien plant species in Germany; estimated at 32 € M per annum or 20% of all alien species costs to that country (F. Klingenstein, pers. comm.). Seeds are dispersed along transport axis, river systems and through soil movement and irrigation activities.

Existing and potential biological control

Biological control projects in Russia, former Yugoslavia, Australia and China have involved releases of seven arthropod agents. The chrysomelid beetle *Zygogramma suturalis* (F.) (Reznik *et al*., 1994) and the noctuid moth *Epiblema strenuana* (Walker) have been the most effective. The beetle can cause high damage in areas with low predation pressure, but does not reduce plant density, which drives the beetle's dynamics. The moth can also be damaging, but has a broader host range including other *Ambrosia*, and *Xanthium* spp. (one native species in each case in Europe). Other released insects include: a homopteran, *Stobaera concinna* (Stal), a beetle, *Trigonorhinus tomentosus* (Say), a fly, *Euaresta bella* (Loew) and another moth, *Tarachidia candefacta* (Hübner), but all these failed to establish.

Carpobrotus edulis *(L.)* L. Bolus

Carpobrotus (Aizoaceae) contains 30 species originating from South Africa, Chile (one species), California (one species) and Australia (four species) of which four are considered weeds worldwide. *Carpobrotus edulis* and the closely related *C. acinaciformis* (L.) L. Bolus are the dominant invasive species around coastal Europe from South Africa. However, two other species and hybrids are also naturalized: *C. aequilaterus* (Haw.) N.E. Br. (Spain) from Chile and *C. glaucescens* (Haw.) Schwantes (UK) from Australia. The genus is exotic to Europe.

Origin, life history and ecology

Carpobrotus spp. are dense mat-forming succulents (chamaephytes) that are invasive mainly in coastal habitats, away from direct salt spray and waterlogging, on most soil types. Inland expansion is limited by cold temperatures. *Carpobrotus* spp. reproduce by selfed or outcrossed (insect pollinated) seed or by vegetative spread. Fruits are attractive to vertebrates which, together with ants, spread the seeds.

Distribution and importance

Introduced into Europe via botanical gardens in Holland and the UK around 1690, it was first observed naturalized in Guernsey in 1880. It now invades suitable habitats from Ireland to Cyprus and the Atlantic Islands. It has been spread, largely deliberately, around the Atlantic and Mediterranean coasts and is a top 10 weed on Mediterranean islands. Main impacts are smothering, reduced pollination and reduced regeneration of native flora (frequently including rare coastal species) and changes to soil nutrients and pH reduction. Over small sensitive areas, *Carpobrotus* spp. can be expensively managed by manual pulling. Success or removal is enhanced by revegetation with native species and with parallel programs for eradicating exotic vertebrate vectors.

Existing and potential biological control

Biological control has not been considered for *Carpobrotus* spp., however agents with specificity to the level of the genus might be in demand. The worldwide distribution of *Carpobrotus* spp. offers the potential for international collaboration.

Heracleum mantegazzianum *Sommier & Levier*

Heracleum (Apiaceae) contains *c*. 60 species originating from temperate Eurasia and North America (five in Europe) of which nine are considered weeds worldwide. *Heracleum mantegazzianum* predominates in Northern Europe (and North America) amongst at least three other closely related species (*H. giganteum* Fischer, *H. lehmannianum* Bunge and *H. persicum* Desf. ex Fischer) that are invasive to a much lesser degree, but poorly documented. *Heracleum lanatum* Michaux from North America and *H. pubescens* (Hoffm.) Bieb. from Asia may also be naturalized in Europe.

Origin, life history and ecology

Heracleum mantegazzianum is a very large short-lived monocarpic perennial herb (hemicryptophyte) with a large deep rootstock. These species originate from the western Caucasus Mountains. Plants flower in about the third year. Reproduction is entirely by seed (*c*. 10 000 per plant), which are dispersed by wind and water and set up only a short-lived 1- to 3-year seedbank (L. Moravcova, pers. comm.). *Heracleum mantegazzianum* is typical in unploughed grazed pastures, meadows, riparian areas, fallow areas and forest clearings, preferring areas of high humidity and nitrogen-rich basic soils.

Distribution and importance

Heracleum mantegazzianum was introduced into Western Europe via botanical gardens in the 19th century (Clegg & Grace, 1974), although in Eastern Europe such species were grown for fodder reflecting its value in the Caucasus. They now present a significant problem in the Atlantic and continental areas of Northern Europe including Ireland, UK, France, Sweden, Denmark, Germany, Poland, the Czech republic and the Baltic states, having spread rapidly along roadsides and rivers in recent years following local disturbance (Pyšek, 1991). The plant is fast growing and highly competitive in pasture and riparian settings, quickly dominating the local flora (Pyšek & Pyšek, 1995). The presence of furanocoumarins in the sap leads to phytophototoxic skin reactions on contact in the presence of sunlight (Drever & Hunter, 1970). Current control measures include grazing, spraying and manual removal (Nielsen *et al*., 2005). Annual control and impact costs in Germany were estimated as 12 € M (Reinhardt *et al*., 2003), where landholders consider it their worst weed.

Existing and potential biological control

Already considered as a target for biological control under the EU FP5 framework funded 'Giant Alien' project, the natural enemies of species in the *H. mantegazzianum* group in the native range have been catalogued. One potential agent that the project focused on was the plant pathogen *Phloeospora heraclei* (Lib.) Petr., however the potential of this agent to infect parsnip (*Pastinaca sativa* L.) has been identified. The presence of other potential biological control agents is being determined, although results are not very encouraging given the close relatives native to Europe (CABI, 2005).

Solanum elaeagnifolium *Cav.*

Solanum (Solanaceae) contains *c*. 1400 species (three European) worldwide of which 143 are considered weeds. *Solanum elaeagnifolium* is the most widespread temperate weed in the genus and 12 of the 15 species in Europe are also exotics mainly from the Americas.

Origin, life history and ecology

Solanum elaeagnifolium is a rhizomatous perennial herb (geophyte) to 60–90 cm, native of North and South America (probable centre of origin is SW USA or N Mexico; Boyd *et al*., 1984). The plant grows under a wide range of environmental conditions and reproduces by seeds and rhizomes. Dormant seeds provide a long-lived seedbank from which seedlings establish intermittently from spring to autumn.

Distribution and importance

Considered in the top 20 weed list in the Mediterranean islands, it has also become a major problem since the 1970s in Greece, Italy and Spain, but also in Israel and from Egypt to Morocco, where it is the fastest spreading new invasive plant (Bouhache & Tanji, 1985; A. Taleb, pers. comm.). It is also a major problem in parts of North and South America, India, South Africa, and Australia. It is a low tillage crop weed causing up to 50% wheat yield loss (Boyd *et al*., 1984) and a pasture weed also infesting meadows and roadsides, where spread is assisted by soil movement and regeneration from small root fragments caused by cultivation or disturbance. Fruits and foliage are poisonous to livestock.

Existing and potential biological control

Native range surveys of *S. elaeagnifolium* have been carried out by various agencies and more than 116 arthropods were collected (e.g. Wapshere, 1988). The South African Plant Protection Research Institute's classical biological control programme since the 1970s has released four insect agents: two fruit-galling gelechiid moths (*Frumenta nephelomicta* Meyrick & *Frumenta* sp. nov.), which failed to establish, and two chrysomelid beetles (*Leptinotarsa texana* Schaeffer & *L. defecta* Stål), which established and led to *L. texana* becoming a patchy but effective agent, locally reaching very high densities. Risk assessment of *S. elaeagnifolium* agents took 6 years due to the economic importance of crops in the genus (e.g. aubergine, potato, tomato) and the presence of major pests in the genus *Leptinotarsa* [e.g. *Leptinotarsa decemlineata* (Say)]. The testing showed that starved beetles feed on native and cultivated *Solanum* spp., but predicted that these species were unlikely to be attacked in the field. Twenty years after release, field evidence confirms this (Olckers *et al.*, 1999). A leaf and stem-galling nematode, *Orrina phyllobia* Thorne, has also been considered as a biocontrol agent (Roche, 1991).

Baccharis halimifolia *L.*

Baccharis (Asteraceae) contains *c.* 350 species from the Americas of which 25 are considered weeds worldwide. *Baccharis halimifolia* is the only species in the genus in Europe where it is invasive in France and Spain.

Origin, life history and ecology

This dioecious, frost and salt tolerant shrub (phanerophyte) of 1–3 m is native to the US coastal plains and interior wetlands from Virginia to Texas. It grows in open woods, thickets and borders of marshes near the coast, often in saline soils. Most germination occurs in autumn–winter with first flowering in the second year. Mature plants can produce up to half a million seeds.

Distribution and importance

Introduced in the 1700s as an ornamental, it invades similar habitats in Spain and France to those occupied the native range, being equally invasive in Australia and New Zealand. It invades disturbed areas and overgrazed pastures, competing with beneficial pasture species.

Existing and potential biological control

The Australian biological control program against *B. halimifolia* between the 1960s and 1990s, released 13 insects and one pathogen of which seven established. These include a gelechiid moth (*Aristotelia ivae* Busck), a bucculatricid moth (*Bucculatrix ivella* Busck), a pterophorid stem-boring moth [*Hellensia balanotes* (Meryrick)], a cerambycid beetle [*Megacyllene mellyi* (Chevrolat)], a cecidomyiid gall midge (*Rhopalomyia californica* Felt), a chrysomelid beetle [*Trirhabda bacharidis* (Weber)] and the groundsel bush rust (*Puccinia evadens* Harkn.). *H. balanotes*, *M mellyi*, *R. californica*, and *T. bacharidis* have led to successful control, especially in habitats similar to those invaded in Europe, to the point where its weed status has dropped. The rust is also useful as both a leaf and stem pathogen, causing defoliation in summer and winter and stem dieback in summer.

Hydrocotyle ranunculoides *L.f.*

Hydrocotyle (Apiaceae) contains 75 species (one European) worldwide of which 25 are considered weeds. *Hydrocotyle ranunculoides* is a cosmopolitan species native to Africa, the Americas and the Middle East. It is an increasingly invasive species in Europe and Australia.

Origin, life history and ecology

Hydrocotyle ranunculoides is a stoloniferous low-growing perennial aquatic with slender rootstocks (hydrohemicryptophyte) that can exist as a floating or emergent aquatic and covers slow moving water. The plant establishes from seed or by rooting from nodes, root and stem fragments. Stolons can grow 15 m out from the bank in a single season, leading to infestations up to 10 km in length (T. Renals, pers. comm.). When protected within other vegetation, it is able to tolerate even severe frosts (Baas & Duistermaat, 1999).

Distribution and importance

Introduced to the UK in the early 1980s, *H. ranunculoides* has increased from 29 sites in 1999 to over 70 sites by 2001. It is also growing in importance in Spain and Italy (including Sicily and Sardinia). It is included on the EPPO (2005) Alert List and sale is prohibited in the Netherlands.

Existing and potential biological control

Baas and Duistermaat (1999) conclude that *H. ranunculoides* is very unlikely to be controlled by conventional means. Cordo *et al.* (1982) highlight a weevil (recently renamed *Listronotus elongatus* Hustache) with an apparently restricted host range from Argentina as a potential biological control agent. A survey by CABI and the UK's Centre for Aquatic Plant Management is planned to search for this and other potential natural enemies.

Ludwigia grandiflora (Michx.) Greuter & Burdet and *L. peploides* (Kunth) P.H. Raven

Ludwigia (Onagraceae) contains 75 species (one European) worldwide of which 30 are considered weeds. *Ludwigia grandiflora* and *L. peploides* (native to the Americas) are the two invasive species in Europe.

Origin, life history and ecology

Both *Ludwigia* species are morphologically similar and native to the Americas being aquatic perennial herbs (hydro-hemicryptophytes), growing rapidly to high density as either emergent or floating-stems. The plant flowers throughout the summer and reproduction is by seeds and plant fragments.

Distribution and importance

Both *Ludwigia* spp. are of equal importance if not fully sympatric in their European distribution. *Ludwigia* spp. are currently only a major problem in France, where they were introduced as ornamentals in the 1820s, but remained for a long time restricted from the Camargue to Aquitaine. They are now rapidly spreading north, but have only been recorded at a few sites in Belgium, the Netherlands, Switzerland, UK, and Spain. The rapid and extensive development of plant populations can block slow-flowing waterways (disturbing many human activities: navigation, hunting, fishing), as well as affecting irrigation and drainage in lakes, ponds and ditches, reducing biodiversity and degrading water quality. Biomass can double in 15–20 days in slow-flowing water bodies and in 70 days in rivers.

Existing and potential biological control

Lysathia ludoviciana Fall has been used a potential biological control agent for *L. peploides* in the USA, where it significantly reduced biomass (McGregor *et al.*, 1996). Another chrysomelid (*Altica cyanea* Weber) has also been considered for the biological control of *Ludwigia* spp. in China, but it feeds on two other species found in Europe (*Trapa natans* L. and the exotic *Rotala indica* (Willd.) Koehne; Shui, 1990). Cordo and DeLoach (1982) collected three curculionids, two *Tyloderma* spp. and adults of *Auleutes bosqi* Hust. that appear to be monospecific, from the leaves of *L. peploides*. Another curculionid, *Onychylis* near *O. nigrirostris* (Boh.) was also collected on *L. peploides* and *Eichhornia crassipes* (Mart.) Solms (waterhyacinth). Mycoherbicides based on strains of *Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc. have also been considered (Jensen, 1991). Three chrysomelid beetles, two *Lysathia* spp. and a *Macrohaltica* sp., and the sphyngid moth (*Pholus fasciatus* Miller) damage *Ludwigia* spp. in Colombia (Cuevas Medina, 2000).

Crassula helmsii (Kirk) Cockayne

Crassula (Crassulaceae) contains *c.* 200 species worldwide (four European), of which 23 are considered weeds. *Crassula helmsii* from Australia and New Zealand is a major invasive species in the UK. *Crassula campestris* (Ecklon & Zeyher), a South African species, is naturalized in Spain.

Origin, life history and ecology

Crassula helmsii has its origins in either Australia or New Zealand, where it is either scarce or poorly documented (Allen, 1961). Populations may be one introduction from the Murray River in Australia (Dawson, 1994). Once established the plant can exist as an emergent form on damp ground or as a submerged form down to 3 m, although the submerged form is not known in the native range (Dawson & Warman, 1987). Dispersal is through fragmentation with tiny sections able to generate new plants. White or pinkish flowers appear in Europe between July and September without production of viable seeds (EPPO, 2005).

Distribution and importance

Crassula helmsii arrived in the UK in the 1950s, but invasions on the continent are more recent (e.g. 1995 in the Netherlands, Brouwer & den Hartog, 1996). It can grow throughout the year and is capable of invading ponds and drainage ditches, smothering native vegetation and creating impoverished ecosystems in vulnerable conservation areas (Manchester & Bullock, 2000; Leach & Dawson, 2001). The plant is tolerant of chemical herbicides (Dawson, 1994). Like *Azolla* it can be mistaken for dry land with associated dangers for animals and humans.

Existing and potential biological control

Few natural enemies are reported in the literature and the plant is known to become an occasional problem in Australia. A biological control programme would need to consider consequences for the closely related and protected UK native, *C. aquatica* (L.) Schonl., despite an allopatric distribution caused by different habitat preferences (Shaw, 2003).

Elodea canadensis Michaux

Elodea (Hydrocharitaceae) contains 12 species from the Americas of which five species are considered weeds. *Elodea canadensis* and *E. nuttalii* (Planchon) H. St John from North America are the most widespread in Europe in that order. However, the more short-lived species, *E. callitrichoides* (Rich.) Caspary, is also naturalized.

Origin, life history and ecology

Elodea spp. are rooted dioecious floating perennial aquatic herbs (hydrophytes) of lakes, reservoirs and fast flowing steams in temperate to tropical climates. In temperate regions, *Elodea* spp. over-winter either as seeds or dormant shoots and turions. Active growth (above 15°C) quickly produces a thick-branched mat over the summer. Reproduction is largely vegetative through stem fragmentation dispersed along watercourses, as stems break easily at the nodes. Horizontal stolons extend the vegetative mat, while vertical stems, arising from the stolons and turions, anchor the plant to the riverbed.

Distribution and importance

Introduced in the mid-1800s, *E. canadensis* infested river systems throughout Europe in the latter half of the century and now occurs in many other countries worldwide. It is a top 10 weed in the UK, France and Germany. During the 1900s, *E. nuttalii* invaded and is replacing *E. canadensis* in many regions. *Elodea callitrichoides* is still more restricted (first found in 1940s). Infestations block water flow and river traffic and interfere with hydroelectric output and urban water supplies. Infestations also reduce light intensity, temperature, oxygen levels and pH of the surrounding water. This affects all aspects of the river communities from native plant diversity to fish numbers. Only female *E. canadensis* plants have been found in Europe, so arrival of males might allow seed production.

Existing and potential biological control

Most species in the Hydrocharitaceae in Europe are exotic, making *Elodea* spp. quite taxonomically isolated compared with the native flora. *Elodea* spp. are also weeds worldwide allowing for international collaboration. In Europe, targeting the whole genus over its broad climatic range would be necessary to prevent weed replacement.

Myriophyllum aquaticum *(Vell. Conc.) Verde (=* M. brasiliense*)*

Myriophyllum (Haloragaceae) contains *c.* 40 species (three European) worldwide, of which 19 are considered weeds. *Myriophyllum aquaticum*, from tropical and subtropical South America is the dominant invasive species in Europe, although *M. heterophyllum* Michaux is also naturalized in Spain.

Origin, life history and ecology

Ecologically and climatically similar to *Elodea* spp., it roots from the nodes and spreads vegetatively via stem fragments. It differs in its preference for stagnant to slower moving shallower water bodies ($<$ 1.5 m) and can move out onto adjacent marshy areas. Stems can also extend above the surface of the water (up to 40 cm) and it is limited in density by light and nutrient levels.

Distribution and importance

First deliberately introduced into France (1880) and then Portugal (1935) as an aquarium escapee, *M. aquaticum* is now also in the UK and is probably more widespread, as it is still sold as an 'oxygenating plant'. It is also a major weed in USA, Australasia, South Africa and Asia. As growth is temperature dependent, it is a bigger issue in milder regions. It affects drainage, river navigation, recreational fishing and native biodiversity. Breakaway floating mats can block pumps in hydroelectric plants. Like *Elodea* spp., all flowers observed in the exotic range have been female, so the arrival of male plants would pose a considerable threat.

Existing and potential biological control

In South Africa a chrysomelid leaf beetle (*Lysathia* sp.) from Brazil has been released and severely retards weed growth. This beetle has been shown not to feed on the European native *M. spicatum* (Cilliers, 1999a,b), suggesting a potential for use in Europe. The ability of the weed to recover from beetle attack as numbers decline, has led to work on two additional agents: the stem boring weevil, *Listronotus marginicollis* (Hustache) and the bacterial wilt disease *Xanthomonas campestris* (Pammel) which already exists in South Africa.

Solidago canadensis *Ait. and* S. gigantea *Ait.*

Solidago (Asteraceae) is largely North American containing *c.* 100 species (one European; *S. virgaurea* L.) of which 21 are considered weeds worldwide. *Solidago canadensis* in Europe (most similar to *S. canadensis* var. *scabra* (Muhl.) Torr. & Gray) is synonymous with *S. altissima* L. (Weber, 2001; Muller, 2004). In addition to *S. gigantea* (which is as important as *S. canadensis*), *S. graminifolia* (L.) Salisb. is also widespread and four other species have naturalized: *S. sempervirens* L. (Azores only), *S. cacicola* (Fern.)Fern., *S. odora* Aiton, and *S. rugosa* Miller. *Solidago nemoralis* Ait., a casual in the UK, is on the EPPO (2005) alert list in anticipation of a range expansion.

Origin, life history and ecology

These *Solidago* spp. are tall perennial rhizomatous herbs (geophytes) to 0.5–2.5 m with erect simple stems producing pyramidal panicles of yellow flowers from August to October. The wind-dispersed seeds are primarily important for long-distance dispersal; for local spread, plants multiply almost exclusively vegetatively, forming dense clonal stands.

Distribution and importance

This garden escape has been commonly cultivated since the mid-1700s and only started to spread widely after a 100-year lag phase. The three main invasive *Solidago* spp. in Europe are still spreading across their potential climatic range (Weber, 2001). *Solidago gigantea* is highly invasive in central Europe, where it can become dominant at forest edges, wetlands and riverbanks, spreading along rivers through rhizome fragmentation. *Solidago canadensis* is invasive throughout Europe (except the north), spreading rapidly through vegetative growth from clonal clumps which can remain dominant, and through abundantly produced wind dispersed seed (Weber, 2003). These *Solidago* species dominate the landscape in permanent grasslands, where they can halve the number of native species within infestations (Muller, 2004). *Solidago* spp. are a top 5 weed in most of central Europe (F. Klingenstein, pers. comm.) and a top 20 weed in France due to their economic and ecological impacts.

Existing and potential biological control

These *Solidago* spp. host over 100 phytophagous insect species in the native range (Root & Cappuccino, 1992). This community has been used as a model ecological system in plant–insect interactions research. Cappuccino (2000) generated an insect list in the context of potential biocontrol effectiveness, based on a capacity to outbreak. Any potential biological control agent for these *Solidago* spp. in Europe would have to leave the common native species, *S. virgaurea* L., relatively untouched. In this context four of the species on Cappuccino's (2000) list may be specific enough, due to their intimate association with their host pant: these are specific host races of a tephritid gall-fly, *Eurosta solidaginis* Fitch (How *et al*., 1993), a gelechiid galling moth, *Gnorimoschema gallaesolidaginis* Riley and two tortricid moths, *Phaneta formosana* (Clemens), *Epiblema scudderiana* (Clemens). *Solidago gigantea* from the exotic range are larger and grow denser than conspecifics in the native range (Jakobs *et al*., 2004). The natural enemy release hypothesis (Keane & Crawley, 2003) is likely to be part of the explanation, as native range studies showed that European-derived plants were more susceptible to insect herbivores than native plants (Meyer *et al*., 2005).

Constraints to the successful implementation of classical biological control in the EU

There are three constraints likely to compromise adoption of classical biological control of weeds in Europe: (i) public perceptions, (ii) funding reliability and (iii) legislative and regulatory issues.

Public perception and risk communication

The public generally has a poor understanding or awareness of the problems caused by alien invasive species (although this is improving) or of the historic and continuing role it plays as a vector of invasive alien plants. The political class in Europe now appreciates the economic impacts and how these are likely to increase as land and agrochemicals are taken out of production. Preventative measures against invasive plants are being used through legislation in other countries (see Box 1, and prohibited movement and trade of ornamentals that

Box 1 Alternate models for national strategies to limit the movement of pest organisms

International Plant Protection Convention guidelines and Sanitary and Phytosanitary measures to assist with international obligations have to link into National plant protection and environmental protection legislation regarding the importation of exotic organisms. These types of national legislation have the option of two generalized alternative approaches.

Innocent until proven guilty – black or prohibited list approach

The IPPC and majority of countries including the EU define a prohibited list of pest organisms that cannot be imported into a country without application of quarantine regulations (the so called 'black list'). These lists of quarantine species prevent the need to determine whether or not each species new to a country should be classified as a pest. Any species not included on that list may be imported assuming it does not harbour a restricted species. This is the innocent until proven guilty philosophy and allows huge numbers of organisms to enter the EU without the need for formal quarantine assessment. Effectively this leaves the door wide open to any potential invasive alien species that has not been included on the list and closing this door is a focus of the ESIAS (Genovesi & Shine, 2004).

Guilty until proven innocent – white or permitted list approach

An alternate model is increasingly being adopted in countries severely affected by and concerned about the impacts of invasive species, notably Australia (Walton, 2001) and New Zealand (Williams, 2003). This model adopts the guilty until proven innocent philosophy such that a list of species that may be imported is defined (the so called white list) and only species on that list may be imported without a permit. Species not on that list may not be imported and may only be imported once a successful application has been made to include the proposed species on the permitted list via pest categorization. The application includes a full pest risk analysis. One advantage of the involvement of a permitted list is that it automatically triggers a pest risk analysis for all proposed organisms not on the list. Such countries nonetheless maintain a prohibited list of quarantine organisms that are known pests that have not yet passed their borders.

are known invaders). Reducing this 'propagule pressure' is a key goal of the European Strategy for Alien Invasive Species (ESIAS; Genovesi & Shine, 2004), but given the long lag phases in plant invasions there are plenty of naturalized known weed species already present that have yet to enter their spreading and invasive phases.

Classical biological control provides a vital curative, albeit long-term, strategy and can only play a part in Europe if the public and its elected politicians are sympathetic to its use. General public understanding of the science behind biological control and the risks and potential benefits is unsatisfactory. For example, the gardening public, concerned about chemical use, is often happy to purchase even exotic biological control agents to control their glasshouse pests. Ask the same people whether they think the government should introduce exotic organisms to counter invasive weeds in their nearby river systems and their judgement may well differ. As politicians respond to the social values of the day, stakeholders engaging and educating the public in the benefits and risks of biological control and listening and responding to their concerns will be extremely important. Generally, the public and their representatives have become increasingly conservative, precautionary and risk averse as the level of human-induced environmental degradation has increased. They would often prefer to do nothing than take risks, yet in the case of invading alien plants doing nothing is not a low risk option. As has been seen in the genetically manipulated organism debate in Europe, the manner in which this knowledge transfer and associated debate is facilitated will be crucial to the level of acceptance. While issues relating to the use of biological control should gain public acceptance more easily, given its more ecological basis and long history of significant successes, sections of the public and their representatives may still remain hostile to any proposed deliberate introductions of exotic insects or pathogens.

Human nature is also biased with respect to appreciation and acceptance of organisms across different taxa. Plants are generally seen in a much more favourable light than insects or diseases. Most invertebrates are considered troublesome or provoke, what in a modern context is, irrational fear. Relatively few are appreciated for their use or beauty. This becomes more acute with respect to pathogens and diseases, where even the terms have negative connotations and led Freeman and Charudattan (1985) to coin the term 'pathophobia'. A new invasive disease or insect pest will always be perceived by the public as higher risk than a new invasive plant. The false perception that plants are easier so manage, based on ease of detection and rate of growth and spread, generally leads to a slower and smaller public response. The error of this is shown in the higher global impacts of weeds (Pimentel, 2002).

More recently, classical biological control of weeds has also undergone significant criticism from within the ecological and evolutionary scientific community (Louda *et al.*, 1997; Strong, 1997), despite there being only a few predictable non-target impacts and the release decisions for the causal agents being made at a time when society was more risk accepting. Healthy scientific debate is crucial for progress, but scientists have lost public trust over the 20th century and such discussions are observed with suspicion and scepticism. What is lost in the arguments and perceptions, however, is that in order to achieve the current societal goals of reduced impacts of invasive species through the Convention on Biological Diversity (CBD), classical biological control can provide environmentally benign solutions and may be the only option in many cases. Whatever the endpoint for Europe, experience from other countries such as New Zealand shows some public consultation on the release of any new exotic organism is important within a balanced decision-making process based on benefits, risks and costs (Sheppard *et al.*, 2003).

The *F. japonica* biological control programme in the UK is one example that appears to be gaining widespread public support. Constructive and balanced media interest has helped the public understand that, while doing nothing is not an option, the programme has no commercial aims or commitment to release agents. Its scientists simply aim to conduct a precautionary-based risk analysis whose merits will be assessed by the relevant authority (cf. Lonsdale *et al.*, 2001).

Funding

In many countries the question of who has responsibility for funding invasive weed management remains unclear (Ghosheh, 2005). Until governments take on assisting and managing this responsibility, funding for classical biological control will continue to prove hard to obtain. Stakeholders who suffer losses due to invasive species should logically drive the funding of biological control programmes. In the case of agricultural weeds, stakeholders are easy to identify. This is not the case for environmental weeds. The long-term nature and lack of immediate benefits from a classical programme further reduce interest and uptake. As the practice of classical biological control offers little or no commercial return (i.e. re-applications of biological control agents are of only limited relevance as effective long-term control arises from natural population growth and spread of the agents), it falls clearly within a 'public good' type of activity (i.e. it is in everyone's interest to have, but in no one's interest to provide). Classical biological control is often unjustly perceived as costly in its initial stages, with no guarantee of success and will therefore only really be possible with direct or indirect government support. For environmental and urban weeds this is even more apparent, so funding of biological control can only proceed with sympathetic, informed and 'joined up' government. Such issues are not unique to biological control, however, as many forms of natural resource management have long-term benefit timeframes and require political incentives for their adoption.

Fortunately, there is also now a groundswell of interest in European Governments over the invasive species issue, partly due to their CBD commitments and a growing recognition that many species and their associated costs are getting out of control. In order to secure funding, the responsible government department(s) [often both the agricultural and environmental ministries (Sheppard *et al.*, 2003)], need to be convinced of the high benefit–cost ratios of biocontrol, and it is here where stakeholders need to work with economists, as the analyses usually fall out heavily in favour of undertaking a biological control programme (e.g. CIE, 2000; Jetter, 2005).

The legislative and regulatory framework for biological control in the EU

Shaw (2003) considered the challenges facing classical biological control in the UK and most of them apply equally well to Europe. The currently inconsistent division of responsibilities across government departments and regional versus national authorities in the EU makes effective control of invasive alien species a real challenge (Genovesi & Shine, 2004). This situation reduces the ability of any nation to produce a rapid eradication response to a new invader, increasing the likelihood of a full-scale invasion. This puts Europe in even greater long-term need for solutions like biological control to its current and future biological invaders. However, the lack of government structure that exacerbates this problem also hinders solution development through unclear funding channels and departmental responsibilities (Ghosheh, 2005). This is exemplified by the current *F. japonica* biological control programme in the UK, which is currently funded by a consortium of six partners after more than a decade of project development efforts.

Plant pathogen biocontrol agents and EU directive 91/414/EU as updated by Council Directive 2005/25/EU

The governmental responsibility and regulatory framework that exists in the EU presents the use of plant pathogens in classical biological control with the exact opposite of the funding problem, by providing one central EU directive hindering their use. Although aimed at minimizing the use of chemicals by regulating 'the placing of plant protection products on the market', the EU directive for chemical pesticide regulation 91/414/EU was originally written in such a way to include, by default, microorganisms as classical biological control agents, while at the same time being inappropriate. For example, the definitions section of the directive begins with a reference to the form in which plant protection products are supplied to 'the user' and the whole process revolves around 'label claims', yet there is no supply to users in classical biological control and no labels. That no specific consideration was given to microorganisms as classical biological control agents is perhaps not surprising, since, with no cases of classical biological control of weeds in Europe, the regulations for such cases would not have been anticipated. This situation, however, has been identified by Seier (2005) as totally inadequate.

A highly specific obligate plant pathogen released once in order to provide permanent control of the target weed generates no subsequent sales, but must still go through a regulatory assessment application designed for commercial non-specific herbicides. Such applications also require formal scientific data largely inappropriate (e.g. mammalian toxicity) or near impossible to obtain *a priori* (e.g. field efficacy versus current chemical alternatives) for the use of pathogens as classical biological control agents. The registration costs are also high, although some EU countries will reduce the costs of application – the UK currently has a pilot scheme with dossier assessment costs of £23 000 (*c.* 33 400 €). Such classical biological control agents are rarely 'silver bullets' but are normally used with a view to *reducing* chemical inputs, in line with a stated EU aim of 'reduction of chemical inputs to the environment', and yet such agents are blocked by inadequacies in the legislation aimed at stricter assessment of new pesticides. The consequence of 91/414/EU is wide-reaching and could prevent the use of plant pathogens in classical biological control in Europe, despite an impeccable worldwide safety record (Barton, 2004) and high levels of effectiveness (Charudattan, 2005).

Recent reviews of the 91/414/EU directive have split consideration of chemicals from microorganisms; however it would seem that entomopathogenic nematodes have been included with microorganisms, which could be considered another step in the wrong direction. There is clearly a need for a new directive or revisions covering classical biological control agents. As this would take considerable time, an interim measure would be for member states to apply the directive to only 'formulated products', thereby distinguishing between microorganisms considered for commercialization (requiring labels and storage information) and classical pathogen agents to be released once or only a few times in the public interest.

Arthropod biocontrol agents and EU directive 2000/29/EU

EU member countries are much freer to do as they wish for biological control using arthropods, indeed perhaps too free. European directive 2000/29/EU protects Europe against introductions and spread of black-listed known pests and harmful macroorganisms (as defined by the EU and its member countries) by their prohibition. However, any species not on the list (likely including all potential classical biological control agents and many potentially invasive plants) can be introduced without any formal risk assessment (see Box 1). There is, therefore, no EU level provision for assessing releases of beneficial exotic invertebrates, although work underway to harmonize this across the EU and define a 'positive list' of widely used organisms free of adverse effects (Bigler *et al.*, 2005). This goes some way to explaining why there have been 276 releases of 137 species of arthropod biological control agents recorded against arthropod pests in EU countries since 1901 in the BIOCAT database (Greathead & Greathead, 1992, updated to end 2004) and the odd negative spill-over effect for these agents (e.g. Roy *et al.*, 2005). Given this, it is perhaps even more surprising that no arthropods have been released against a target weed. An explanation comes from an inherent greater general precaution over releases of herbivorous versus entomophagous arthropods because, as in the USA, the release agency would be legally responsible should any biological control agent cause economic loss or significant environmental damage (Miller & Aplet, 1993; Delfosse, 2005).

Each EU member state transposes and interprets the European Directive 2000/29/EU directive into their national legislation and this is leading to a process of developing regulatory procedures for the releases of invertebrate biological control agents (Genovesi & Shine, 2004; Bigler *et al.*, 2005). Currently, there remains a wide divergence in such regulatory requirements. Of 19 countries surveyed, eight had implemented regulations, five were in the process of implementing them and six, including France and Italy, without regulations (Bigler *et al.*, 2005). The UK and Portugal are the two countries currently most advanced in classical weed biological control research programmes. While the UK has such regulations in place, Portugal still does not.

EU countries should use the EPPO (2000) standards and the newly revised international advisory 'Guidelines for the Export, Shipment, Import and Release of Biological Control Agents and Organisms Claimed to be Beneficial', otherwise called the International Standards for Phytosanitary Measures, publication No. 3 or ISPM 3 (Kairo *et al.*, 2003; Genovesi & Shine, 2004; IPPC, 2005), which also highlights the need for consultation between relevant neighbouring countries. ISPM 3 is also inclusive of fungal agents, i.e. non-formulated microorganisms that are released with the expectation of establishment. It follows, therefore, that any National regulatory procedures developed by EU member states for the release of classical biological control agents, as a result of EU directive 2000/29/EU, and based on ISPM 3, should be technically capable of including both macro- and microorganism agents.

The CBD and the ESIAS

Each signatory to the CBD has an obligation to 'prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats and species' (Decision VI/23 in 1992; http://www.biodiv.org/decisions/default.asp?lg=0&dec=VI/23). As part of this, the CBD emphasizes the need for signatories to invest in research and assessment of biological control as a management option. Classical biological control practitioners, as part of their studies, fulfil every requirement under the CBD guiding principle 10, relating to applying the precautionary approach to intentional introductions of exotic organisms. Unfortunately, such rigour is not always employed by other sectors involved in trans-border movement of living organisms (plants in particular). It is no coincidence that the vast majority of invasive plants were introduced for the benefit of the gardener who unwittingly aided the invasion process. That same consumer is now becoming more aware of the impacts of their activities and of the threat posed by invasive species and this needs to pressure the supply chain to stop selling known invasive species and provide more information on the plants being sold.

Many European countries are waking up to the scale and impact of invasive alien species, as highlighted by the recent publication of the ESIAS (Genovesi & Shine, 2004) which aims to stem the flow. This document was developed under the Bern Convention and recommends the requirement of a 'grey list' of species posing unknown threats that need to be screened for risks before introduction, including classical biological control agents under ISPM 3. The structure of the strategy underlines the need for an holistic approach, based on the best use of existing resources (Genovesi, 2005). Only through the consideration and facilitation of classical biological control can countries fulfil their CBD obligations and implement the ESIAS.

Conclusions

Classical biological control offers environmentally sound and public good solutions to some of Europe's worst alien invasive plants. It would assist EU commitments to reducing chemicals in the environment and controlling alien invasive species, while applying the precautionary approach to intentional introductions of such beneficial exotic organisms. Europe has no shortage of potential targets for classical biological control using coevolved exotic natural enemies. Indeed, some of these weeds have been subject to successful biological control elsewhere. This review highlights 20 of these and suggests, with the full support and in the context of the CBD and the ESIAS, the time is ripe for classical biological control of weeds to break into the mainstream, alongside public demand for action and national commitments to reduce chemical use and protect biodiversity. However, this will continue to be delayed if suitable government-assisted funding streams are not established alongside processes for assessing conflicts of interest and raising public awareness on the issue of the costs of invasive species and the available solutions to them. Furthermore, the EU and its member states need to enact legislation and associated regulations as recommended under the ESIAS for restricting the importation of harmful and potentially harmful exotic organisms. Appropriate regulations can still allow releases of beneficial exotic species used in classical biological control, based on ISPM 3 and EPPO standards (2000) of risk assessment. By doing so, the EU would ensure all biocontrol agents proposed for release meet international risk analysis standards. The use of plant pathogens as classical biological control agents in the EU needs to be facilitated more than any other agent type through revision of the 91/414/EU directive, or at least its interpretation by member states, so that it is only applied as originally intended to formulated products. Rapid progress must be made, if all the invasive alien species management tools are to be available and Europe is to catch up with the rest of the world.

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