A global view of the future for biological control of gorse, *Ulex europaeus* L.

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Summary

Gorse (*Ulex europaeus* L.) has become naturalized in at least 50 countries outside its native range, from the high elevation tropics to the subantarctic islands and Scandinavia. Its habit, adaptability and ability to colonize disturbed ground makes it one of the world's most invasive temperate weeds. It is 80 years since New Zealand first initiated research into biological control for gorse. This paper briefly reviews the progress made worldwide since then, and examines future opportunities for biological control of this weed. The range of available agents is now known, and this list is critically assessed. Ten organisms have been released variously in six countries and islands and their performance is reviewed. In most cases, agent populations have been regulated either from 'top-down' or 'bottom-up', and there is no evidence anywhere of consistent outbreaks that could cause significant reduction in existing gorse populations in the medium term. Habitat disturbance and seedling competition are important drivers of gorse population dynamics. Existing agents may yet have long-term impact through sublethal effects on maximum plant age, another key factor in gorse population dynamics. Along with habitat manipulation, seed-feeding insects may yet play a long-term role in reducing seed banks below critical levels for replacement in some populations. In the short term, progress will rely on rational and integrated weed management practices, exploiting biological control where possible.

Keywords: integrated weed management, population dynamics, modelling.

Introduction

Gorse, *Ulex europaeus* L. (Fabaceae), is a thorny shrub native to the temperate Atlantic coast of Europe and the British Isles including Ireland. It has become naturalized elsewhere in Europe, North Africa and the Middle East. In other parts of the world, gorse has proven to be an aggressive invader, forming impenetrable, largely monotypic stands that reduce access of grazing animals to fodder, modify native ecosystems and ecosystem processes, and outcompete trees in developing forests. It has now been recorded in more than 50 countries and islands, and is considered to be a major weed in New Zealand (Hill *et al.*, 2000), the USA (Markin *et al.*, 1995, 1996), Chile (Norambuena *et al.*, 2007) and Australia (Ireson *et al.*, 2006).

Gorse is tolerant of a wide range of conditions, but in temperate latitudes, it is limited altitudinally by cold temperatures. This has not stopped it becoming established in the montane regions of tropical Hawaii, Sri Lanka and Costa Rica, and it grows in Scandinavia, on St. Helena, on some subantarctic islands, and in coastal NE USA, where maritime influences moderate the climate. New Zealand is one of the few places where gorse has largely achieved its maximum distribution.

Land managers on intensively managed land with adequate economic returns have many excellent alternatives for managing gorse. However, biological control may provide the only option for limiting the effects

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of gorse on land that provides low economic returns, land that is managed for biodiversity values, or where the infestation is simply too difficult to manage.

It is now more than 80 years since research into the biological control of gorse in New Zealand was first commissioned (Zwölfer, 1963), and the first biological control agent, *Exapion ulicis* Forster (Brentidae), was first released on Maui, HI, in 1926 (Markin *et al.*, 1996). Ten biological control agents have now been released as classical biological control agents in six countries or regions: two seed-feeding insects and eight organisms that attack green stems (Table 1). It is now time to examine the state of gorse biological control worldwide, and its future role in gorse management. The purpose of this paper is to:

- evaluate the effects to date of biocontrol agents released worldwide;
- examine the options for the development of new biocontrol agents; and
- explore how biological control might interact with other management techniques.

Current role of biocontrol agents in gorse management worldwide

Exapion ulicis (Forster)

The gorse seed weevil, *E. ulicis*, is now widely established in New Zealand, Australia, the USA (the West Coast and Hawaii) and Chile (Table 1). In New Zealand, the weevil only attacks pods in spring, whereas gorse sets seed in both spring and autumn. Where the bulk of annual seed production is in autumn, almost all seeds escape attack. Where the bulk of seed production is in the spring, infestation rates are low because of the abundance of the food source available to the weevil (Hill *et al.*, 1991a). Either way, this results in approximately 65% of the annual seed crop escaping attack (Cowley, 1983). As in New Zealand, Davies (2006) showed that larvae feed on seeds produced in spring and summer in Australia (Tasmania), and were not present during a second period of seed production during autumn and winter. He found that damage to gorse seed ranged from 12.4% to 55.4% and varied annually within and between sites. In Chile, *E. ulicis* is able to reduce gorse seed production and dispersal (Norambuena and Piper, 2000) but has had only limited impact upon gorse invasiveness to date. The same is true in the western United States (Markin *et al.*, 1995) and on the islands of Maui (1953) and Hawaii (1984) (Markin and Yoshioka, 1998).

Cydia succedana (Denis and Schiffermüller)

With the realization that *E. ulicis* alone was unlikely to reduce seed production to low levels at most sites, a strong focus of research and development since 1982 has been the search for new control agents that could augment the activity of the univoltine weevil in spring, and also reduce the autumn seed crop that currently escapes attack. *C. succedana* was chosen for release in New Zealand to fill this role (Table 1) as it has two generations per year in its home range; one in spring on pods of *U. europaeus* and another on pods of late summer- and autumn-flowering gorse species. The moth is now abundant throughout gorse-infested areas of New Zealand. Gourlay *et al.* (2004) used insecticide exclusion to show that *C. succedana* augmented control gorse seed predation by *E. ulicis* and recorded an overall 81% loss in spring seed production at one site. However, the predicted reduction in autumn seed production has not occurred. There appears to be lack of synchrony between the emergence of moths and the peak occurrence of *U. europaeus* pods in autumn, and infestation rates rarely exceed 10%. As seed set in autumn forms the bulk of seed production in warmer parts of New Zealand, adequate control of seed production has not yet been achieved.

Tetranychus lintearius Dufour

Populations of the mite *T. lintearius* (Tetranychidae) initially increased rapidly in the countries where it was released (Table 1). Colonies formed massive webs over gorse and caused severe bronzing of the foliage. However, in New Zealand and Australia, populations have declined at all sites after the initial increase, and although localized outbreaks still occur, widespread outbreaks are now rare. Mite populations in New Zealand appear to be regulated by the predators *Stethorus bifidus* Kapur (Coccinellidae) and *Phytoseiulus persimilis* (Athias-Henriot) (Phytoseiidae).

In Australia (Tasmania), Davies *et al.* (2007) showed that the presence of mite colonies on gorse bushes over a period of 2.5 years from the time of release reduced foliage dry weight by around 36%. However, predation of *T. lintearius* colonies by *Stethorus* sp. and *P. persimilis* is widespread in Australia (Ireson *et al.*, 2003) and probably a key factor in restricting the impact of the mite. *P. persimilis* has been associated with the destruction of entire colonies in both Tasmania and Victoria (Ireson *et al.*, 2003) as well as in Oregon, USA (Pratt *et al.*, 2003).

Regulation by predators does not yet appear to be as severe in Hawaii and Chile. The mite has been abundant in Hawaii since 2000. Chemical exclusion from paired bushes (n = 10) indicated that mite feeding reduced gorse shoot elongation by 37% and flowering by 82% (G. Markin, unpublished data). Similar effects have been measured in unpublished New Zealand studies, but only where infestation is persistent. Predation usually precludes such long-term damage. In Chile, mite populations have grown strongly at 90% of release sites, especially in relatively dry areas, despite predation

Table 1. Status of biological control agents released worldwide against gorse (N = not established, R = recovered, not yet established, E = established, HI = Hawaii, WC = west coast).

Control agent	Taxonomic group	Target country	Date of release	Status (N, R, E)	Comments	References
Exapion ulicis (Forster)	Brentidae	New Zealand	1931	E	Larvae attack seeds in pods	Hill *et al.*, 1991a
		USA, HI	1926	N		
			1958, 1984	E	First on Maui and then Hawaii	Markin *et al.*, 1996; Markin and Yoshioka, 1998
		USA, WC	1953	E		Davis, 1959; Markin *et al.*, 1995
		Australia	1939	E	Established in TAS, VIC, NSW and SA	Ireson *et al.*, 2006
		Chile	1976	E	Seed production and dispersal decreased	Norambuena *et al.*, 1986
Apion sp.		USA, HI	1958	N	Seed in pods	
Eutrichapion scutellare Kirby)	Brentidae	USA, HI	1961	N	Forms galls	Markin *et al.*, 1995
Tetranychus lintearius Dufour	Acari	New Zealand	1989	E	Extracts mesophyll	Hill *et al.*, 1991b, 1993
		USA, HI	1995	E		
		USA, WC	1994	E		Pratt *et al.*, 2003
		Australia	1998	E	Established in TAS, VIC, NSW, SA and WA	Ireson *et al.*, 2003
		Chile	1997	E		Norambuena *et al.*, 2007
			2006	R	Released and recovered at 50 new points between 41º53' and 43ºS	H. Norambuena, personal communication, 2006
		St. Helena	1995	E		S.V. Fowler, personal communication, 2006
Scythris grandipennis (Haworth)	Scythrididae	New Zealand	1990	N	Larvae defoliate from solitary web	Hill *et al.*, 2000
Agonopterix ulicetella (Stainton)	Oecophoridae	New Zealand	1990	E	Larvae defoliate from solitary web	Hill *et al.*, 1995
		USA, HI	1988	E		Markin *et al.*, 1996
		USA WC				Markin *et al.*, 1995
		Australia			Release approved; population ex NZ currently in quarantine F31	
		Chile	1997	R	Recovered the following year but establishment not confirmed; good damage potential in confinement	Norambuena *et al.*, 2004
			2006	R	Released at 40 new points between 41º53' and 43ºS	H. Norambuena, personal communication, 2006
Sericothrips staphylinus Haliday	Thripidae	New Zealand	1990	E	Extracts mesophyll	Hill *et al.*, 2001
		USA, HI	1990	E		Markin *et al.*, 1996; Hill *et al.*, 2001
		Australia	2001	E	Established in TAS and VIC, establishment in NSW and SA not confirmed	Ireson *et al.*, 2006

Table 1. (Continued) Status of biological control agents released worldwide against gorse (N = not established, R = recovered, not yet established, E = established, HI = Hawaii, WC = west coast).

Control agent	Taxonomic group	Target country	Date of release	Status (N, R, E)	Comments	References
Cydia succedana (Denis and Schiffermüller)	Tortricidae	New Zealand	1992	E	Larvae feed on seeds in pods	Hill and Gourlay, 2002
Pempelia genistella Duponchel	Pyralidae	New Zealand	1996	E	Larvae defoliate from communal web	Hill *et al.*, 2000
		USA, HI	1996	R		Markin *et al.*, 1996, 2002
Uromyces pisi (DC.) Otth. f. sp. *europaei* Wilson and Henderson	Uredinales	USA, HI	2000	R	Single pustule after 2 years, but not seen since	Culliney *et al.*, 2003

by *Oligota centralis* Sharp (Staphylinidae). The stress of mite attack has slowed plant growth, flowering has become almost totally disrupted, and occasional seedlings have been killed. The mite is now being distributed widely in Chile (Norambuena *et al.*, 2007), but in Hawaii, populations have declined recently, and it is feared that regulation by a phytoseiid new to this montane region is underway.

Sericothrips staphylinus Haliday

Sericothrips staphylinus (Thripidae) is now widespread in Hawaii and parts of New Zealand, and has now become established in Australia (Table 1). No field studies on the efficacy of this species under field conditions have been conducted. However, a glasshouse study in Australia (Tasmania) showed that a combination of feeding by gorse thrips, ryegrass competition and simulated grazing resulted in a gorse seedling mortality of 93% compared with no mortality in the untreated control, and reduced shoot dry weight of seedlings (Davies *et al.*, 2005). This experiment indicates the potential of *S. staphylinus* in an integrated control programme if field populations are eventually able to increase to sufficient densities. As yet no visible damage attributable to *S. staphylinus* has been observed at Tasmanian field sites up to 6 years after release. The maximum estimated field population density of juveniles and adults has been ca. 1.5 thrips cm^{-1} of new growth. In comparison, population densities of ca. 7 thrips cm^{-1} of new growth have been measured in glasshouse cultures, from plants on which severe feeding damage was recorded (J. Ireson, unpublished data).

Agonopterix ulicetella (Stainton)

Despite heavy parasitism, larvae of the oecophorid moth *A. ulicetella* destroy a high proportion of gorse shoot tips in the Hawaiian infestation each spring. However, the control agent is univoltine, and the period of damage is short. Gorse plants appear to compensate for the loss within the growing season by initiating new shoots, and the effect on growth rate or biomass accumulation per plant is not known. This is also true in New Zealand, where outbreak populations have begun to appear in some sites since 2005, 15 years after the moth was first released. While the moth produced substantial damage to gorse shoots enclosed within a fine mesh sleeve in Chile (Norambuena *et al.*, 2004), field establishment has not been confirmed.

Pempelia genistella Duponchel

A small population of this pyralid moth was observed for several years following its release in Hawaii. No larvae have been detected for some years. Recent applications of herbicides and fire destroyed the original release sites, and the persistence of this species is in doubt. In New Zealand, *P. genistella* has established well at only a limited number of sites near Christchurch, despite widespread releases nationwide (Table 1). The reasons for this are not known, and its future role in gorse management remains uncertain.

Uromyces pisi (DC.) Otth. f. sp. *europaei* Wilson and Henderson

In 2002 a single pustule of this rust was detected in Hawaii near where it was released 2 years previously. It was a new infection locus, and urediniospores were being produced. No additional rust pustules have been found since, so its continued establishment must be in doubt.

Bioherbicides for gorse management

In addition to the classical biocontrol agents, two pathogens are being formulated in New Zealand as bioherbicides of gorse. It has proven difficult to formulate *Fusarium tumidum* Sherb. in a way that produces consistent damage to gorse foliage, but Bourdôt *et al.* (2006) recently showed that both *F. tumidum* and *Chondrostereum purpureum* (Pers.:Fr.) Pouzar may have potential as mycoherbicides for gorse regenerating after mowing or trimming.

Options for the development of new agents

Surveys of potential biocontrol agents for gorse have been conducted in the native range of gorse over a long period. Zwölfer (1963) reported on European literature records, and CABI staff undertook surveys of the fauna in France. Zwölfer's report did not specifically state the time of year of the surveys, but they were generally considered to have been carried out in spring (Sheppard, 2004). R.L. Hill (1982, unpublished results) completed a detailed study of the seasonality of gorse insects in southern England. O'Donnell (1986) surveyed NW Spain and Portugal in spring, listing brief site descriptions and the agent species identified. Other less formal surveys by authors of this paper explored the fauna of gorse as far south as Sintra, NW of Lisbon in spring (R. Hill and G. Markin, unpublished data). Sheppard (2004) combined the information from all of these sources and this summary is now considered to be the definitive list of invertebrates that have potential as control agents for gorse.

The rate at which gorse spreads into new habitats is likely to be strongly related to the amount of seed produced, and reducing the annual seed crop using seed-feeding agents may slow spread and give land managers opportunities to protect vulnerable habitats. *E. ulicis* and *C. succedana* singly and in combination reduce the annual seed crop of gorse in New Zealand (Hill *et al.*, 2004) but not sufficiently to cause population decline (although it is possible that the long-lived seed bank masks such an outcome, and these effects may become apparent in the future). For New Zealand, the solution lies in finding control agents that attack pods formed in autumn. Several *Apion* species are known to take this role (Zwölfer, 1963). *Cydia internana* (Guerin) also fills this role, but this is a rare species in the UK (Hill, 1982). The introduction of *C. succedana* to regions outside New Zealand remains an option, but its unpredicted appearance on hosts related to gorse following release in New Zealand demands caution and further research. Such research is in progress (Fowler *et al.*, 2004).

The introduction of additional seed-feeding agents would also be useful for Australia, especially as there are many sites where gorse sets seed only once per year. The planned introduction of *C. succedana* is now unlikely (Ireson *et al.*, 2006) although it may still be considered once additional data on its true host range and the level of damage caused to alternative hosts is considered. Ultimately, the introduction of an additional seed feeder to Australia may depend on the discovery of host-specific biotypes of known species from Europe, although no such autumn seed feeders were found in recent surveys (Sheppard, 2004). Foliage-feeding agents may also reduce annual seed production by reducing plant vigour, but as yet we know little about the strength of this effect.

The primary aim of the field surveys conducted in Europe during 2003 (Sheppard, 2004) was to identify agents capable of reducing seed production in autumn. There were only low levels of pod production during the period of the survey, and losses of *Ulex* spp. seed to pod moths (*Cydia* spp.) and *E. ulicis* were considered minor. There was also no evidence that there were any other autumn-specific seed-feeding agents active during this period (Sheppard, 2004).

Surveys for root-feeding agents (Sheppard and Thomann, 2005) revealed low levels of damage over a large part of the native range of gorse and it was concluded that this guild of insects is unlikely to contain useful biological control agents.

It is now considered unlikely that additional invertebrate species with potential as gorse biocontrol agents will be found in Europe, although one further survey of insects inhabiting gorse pods in NW Spain and Portugal will be conducted in 2007. Seed produced from flowers set in autumn contribute consistently and heavily to the annual seed crop of gorse in New Zealand and elsewhere, and it is surprising that this resource is not exploited by natural enemies in Europe. In contrast, autumn seed production in Europe appears to be inconsistent, and the stochastic nature of the resource may let these seeds escape predation.

As the most recent surveys have shown that the options for additional invertebrate biocontrol agents are limited, surveys for host-specific fungal pathogens of gorse commenced in the European autumn of 2006 (Ireson *et al.*, 2006). Diseased gorse specimens were collected in SW France, NW Spain and northern Portugal to enable isolation, culturing and identification. Surveys for pathogens will also continue during 2007.

Discussion

Hill *et al.* (2004) pointed out that effective gorse management relies on selecting the most appropriate suite of management tactics for each situation. Where gorse is newly naturalized or of limited distribution, the highest priorities for investment in management should be to determine the extent of the infestation, develop appropriate public policy, contain the distribution, and if possible eradicate the weed. There is little place for biological control here, at least in the short term. Widespread gorse can be managed successfully to protect production or environmental values using conventional methods such as herbicides, although this is expensive and technically difficult. For this reason most gorse infestations worldwide are not managed for economic or environmental gain and yet are already too widespread for containment to be feasible. Biological control appears to be the only means to achieve gorse control in such habitats.

Not all available agents have yet been distributed worldwide (Table 1), but given the lack of immediate success where they have been released, investment in the development of any of these agents should be made only after critical asessment of their potential contribution to gorse management. With the conclusion of recent surveys, our knowledge of the natural enemies of gorse is assumed to be almost complete. Most of the agents identified to date seem to have lower potential for impact, and appear to be less host-specific than those already released, and there appear to be no compelling new candidate agents. In short, there appears to be no 'classical' biological control solution for gorse in areas where management by conventional means cannot be brought bear as well.

Opportunities remain for augmenting and enhancing classical biological control worldwide through integration with conventional management tactics. Spatially explicit simulation modelling showed that seedling survival (in particular the poor ability of gorse seedlings to compete against grasses) and disturbance were key determinants in the population dynamics of gorse (Rees and Hill, 2001). The model predicted that under a limited range of scenarios of high disturbance and high seedling mortality 75–85% reduction in the annual seed production (initially set at 20,000 seeds m^{-2}) as a result of predation by biocontrol agents could lead to a decline of equilibrium cover in the long term.

Davies *et al.* (2005) showed that under laboratory conditions the competitive ability of gorse seedlings growing with grass can be severely reduced by insect attack although this has not been confirmed in the field. The simulation model suggests that by reducing the competitive ability of gorse seedlings in this way, foliage-feeding agents may increase the probability that seed-feeding agents will be effective in achieving long-term control of gorse, bringing the levels of reduction in the annual seed crop required for such control within reach of the known agents.

Gorse population simulations were also sensitive to lifetime fecundity of gorse plants, which is directly related to the maximum age of the plants (Rees and Hill, 2001). None of the control agents released have yet shown a propensity to cause lethal damage to mature plants, but we know little about the chronic effects of these control agents on maximum age in the field. It is possible that sublethal attack may already be reducing the vigour and longevity of gorse, affecting its long-term population dynamics. Additional agents might enhance that effect, even though not greatly damaging in their own right. Management techniques such as the appropriate use of fire, grazing and overseeding may augment this effect (Rees and Hill, 2001; Hill *et al.*, 2004).

High control agent populations that might prove damaging to gorse appear to be constrained from the 'top-down' by predation (in the case of *T. lintearius*), or possibly from the 'bottom-up' by the effect of seasonality and plant quality on the voltinism and intrinsic rate of increase of agents (Hill, 1982; J. Ireson, unpublished data). Even in Hawaii, where predation constraints on *T. lintearius* appear to be absent, severe attack leads to reduction in biomass and flower production, but not plant death. In Australia, the ability of these agents to have any significant long-term impacts on gorse growth and development is considered to be limited without the establishment of additional agents.

The synergy that can exist between conventional control tactics and biocontrol agents in the management of legume shrub weeds such as gorse are clear (Rees and Hill, 2001; Buckley *et al.*, 2004). Integrating weed control techniques may offer the best prospects for long-term control in areas where gorse is actively managed, but the extent to which biological control will play a role in this will only be determined by future research once the full complement of available agents are established.

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