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ORIGINAL PAPER

Assessing the biosecurity risk from pathogens and herbivores to indigenous plants: lessons from weed biological control

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Abstract Some potentially invasive herbivores/pathogens in their home range may attack plants originating from another geographic area. Methods are required to assess the risk these herbivores/pathogens pose to these plants in their indigenous ecosystems. The processes and criteria used by weed biological control researchers to assess the impact of potential biological control agents on a plant species in its non-native range provide a possible framework for assessing risks to indigenous plants. While there are similarities between these criteria such as the need for clear objectives, studies in the native range of the herbivore/pathogen, good knowledge of the ecology of the target plant and taxonomy of the plant and herbivore/pathogen, and modelling of the interaction between the two organisms, there are some important differences in approach. These include the need to consider the threat classification of the plant, the likely greater risk from polyphagous herbivores/pathogens than oligophagous or monophagous species, and the need to consider the impact of an additional natural enemy in conjunction with a suite of existing natural enemies. The costs of conducting a risk assessment of a herbivore/pathogen in another country that damages plants indigenous to another geographic area means that criteria will be needed for deciding which foreign herbivore/pathogen species should be assessed. These criteria could include the threat classification of the plant, the amount of damage to the particular plant organs affected, and the importance in key ecosystems.

Keywords Indigenous plants · Natural ecosystems · Insect herbivores · Mite herbivores · Plant pathogens · Invasive species

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Introduction

Plant pathogens or herbivores entering and establishing in another country/geographic area may attack indigenous plants as well as cultivated and naturalised plants. In the past governments have been primarily concerned about protecting cultivated and beneficial naturalised plants from new pests through a variety of biosecurity measures taken at various points on the pathways followed by at risk goods. These measures include inspection of imported produce and plants before shipment and/or at point of entry, quarantine of live plants before or after entry, and mandatory physical or chemical treatments of plants and produce before or after entry into the importing country (Sumner 2003). The types of treatments reflect the perceived risks and the pathways followed by the goods. Today, many countries are equally concerned to protect their indigenous plants from pests, indeed the International Plant Protection Convention (IPPC), hosted by the Food and Agriculture Organization of the United Nations (FAO), has recently re-interpreted its mandate to include the protection of plants in natural as well as agricultural systems (Waage and Mumford 2008; IPPC 2005).

To protect indigenous plants from herbivores and pathogens from different geographic areas, biosecurity authorities must identify high risk pathways by which these organisms may enter the country and to put in place measures to reduce the risk of entry through these pathways. This requires knowledge of the biology of the organisms in their current geographic areas and an assessment of the likelihood that they will establish in the new geographic area. For crops, there are lists, often extensive, of the kinds of diseases and pests that can attack them, e.g. Crop Protection Compendium (2004), and for many of these pests there is often substantial information about their biology, and potential damage they may cause to crop plants. There are standardised procedures for assessing these risks to crop plants and for identifying pathways into the country (e.g., Anonymous 2006). These procedures include hazard identification, assessing the likelihood of entry, the likelihood of establishment and the consequences of establishment. These procedures are time consuming and may involve preliminary hazard identification and prioritisation. In some countries such as New Zealand, part of the standard procedure includes an assessment of the risk of crop diseases and pests to indigenous plants. An organism that may be a threat to indigenous plants requires information about the impact of the herbivore/pathogen to the plant species in a geographic area where the herbivore/pathogen are present and an assessment of the consequences of establishment of the herbivore/pathogen in the new geographic area for it to be classified as a potential hazard. If the risk is perceived to be high, then a full risk assessment is undertaken which includes pathway analysis and identification of steps to reduce the likelihood of entry and establishment (Anonymous 2006).

There is relatively little information about the susceptibility of indigenous plants to crop pests in the plants home range and even less information about what the impact of herbivores and pathogens living other geographic areas may have on indigenous plants in their home range. One potential source of information about these herbivores and pathogens is to document those found on indigenous plants living outside their indigenous geographic area. A New Zealand government-funded research project "Using expatriate New Zealand flora as predictors of threats to NZ natural ecosystems" (www.b3nz.org/public/natural_ecosystems.php) that was part of the Better Border Biosecurity (B3) programme, aimed to identify foreign herbivores and pathogens that may be harmful to New Zealand indigenous plants in natural ecosystems. It did this through a survey of literature and examination of New Zealand plants growing in other countries by New Zealand researchers visiting plant collections in these countries or by arranging for researchers living in other countries to examine these plants and report on diseases and pests. There was relatively little information about herbivores and pathogens in other countries that could attack plants endemic to New Zealand, though there is more information in the literature about non-endemic indigenous plants (those present naturally in New Zealand and other countries) (Plant-SyNZ database 2009). In summary, the Plant-SyNZ database contains information on 51 herbivores that are not in New Zealand and that could live on 25 species of New Zealand indigenous plants. Nine species of plant are listed as endemic (19 host associations) and 16 species of non-endemic indigenous plants are listed (40 host associations).

Having identified herbivores and pathogens in other geographic areas that live on indigenous plants in the target area, the next step is to determine the risk that these pathogens and herbivores pose to the indigenous flora, especially in their indigenous ecosystems. Some herbivores and pathogens from other geographic areas will already be living in the target geographic area and some will be living on indigenous plants (e.g. Table 1). The extent of their threat to indigenous plants can be assessed in situ. In contrast, for herbivores/pathogens that are not present in the target geographic area, information about the severity of their impact on indigenous plants and their possible impact on indigenous ecosystems must be gathered in other geographic areas where these herbivores/pathogens live. However, if a foreign

Table 1 Summary of adventive herbivores present in New Zealand and found on New Zealand indigenous plants (Plant-SyNZ database Plant-SyNZ database 2009)

Herbivore group	Number of species	Number of indigenous host plant associations		
		Endemic plants	Non-endemic plants	Total
Acari	6	12	3	15
Coleoptera	22	29	14	43
Diptera	6	7	10	17
Hemiptera: Coccoidea	26	195	46	241
Hemiptera: other	50	142	44	186
Isoptera	1	1	0	1
Lepidoptera	12	14	11	25
Thysanoptera	4	30	10	40
Mollusca: Gastropoda	1	2	0	2
Total species/associations	128	452	143	595

herbivore/pathogen is found to cause severe damage to a plant growing in a non-indigenous geographic area, can it be assumed that the herbivore/pathogen will cause equally severe damage to the plant in the plants native ecosystem?

This use of information about herbivore/pathogen interactions with a host plant in one geographic area in order to predict the interactions between the two organisms in another geographic area where one of the organisms is absent, has similarities to the objectives of classical biological control of weeds. Researchers of classical biological control of weeds need to assess the impact of herbivores and pathogens on a target plant in its home range in order to select the natural enemy that will most likely have the desired effect on the target weed in a country where the natural enemy is currently absent. It is important to limit selection to a few, most promising, organisms to reduce the costs of host specificity testing, multiplication and release, and to minimise the risk of non-target effects by minimising the number of organisms released (Raghu and van Klinken 2006). The process of selecting weed biological control agents is reviewed and improvements suggested in a special issue of the Australian Journal of Entomology (2006, vol. 45, part 4). Some of the practices and suggested improvements offer ideas about how to assess the risk from herbivores and pathogens to plants indigenous to other geographic areas.

Most of the papers in the special issue concern herbivores although Morin et al. (2006) discuss the procedures for the selection of pathogens for use as biological control agents for weeds and compare the processes for herbivores and pathogens. This paper considers herbivores and pathogens together as both kinds of organism threaten indigenous plants in their indigenous ecosystems. Research reported here describes each step of the proposed protocol for biological control agents for weeds and identifies the relevant steps and kinds of information needed to assess the risk of herbivores and pathogens in other geographic areas to indigenous plants in their home range.

Defining the goal

Weed biological control consists of a number of steps (Fig. 1), only two of which are relevant to this discussion, exploration and prioritisation of agents.

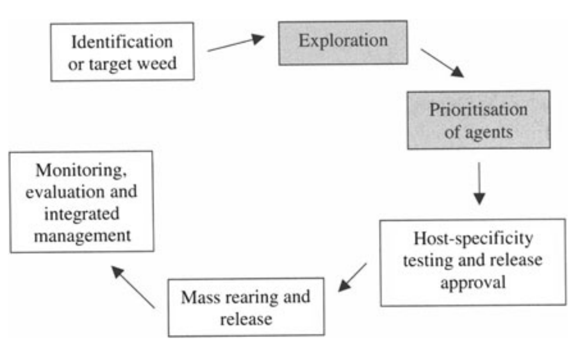

Fig. 1 Steps in biological control practice (from van Klinken and Raghu 2006, Fig. 1, p. 254), *shaded boxes* are relevant to this paper

However, it is important to clearly define 'success' for each biological control programme. This will help provide clear outcomes, a focus for the research and a measure for assessing success (van Klinken and Raghu 2006).

When trying to determine the risk to indigenous plants, clear outcomes also needed. Important factors to consider when defining outcomes are knowledge of the threat status of the target native plant (Table 2), the level of protection required and what that means in terms of damage by pathogens or herbivores that can be sustained with minimal risk (Table 3). Having clear criteria for each plant of concern will enable a better focus on the kinds of data to be collected, the appropriate analysis and modelling as well as the implementation of the most effective measures to prevent entry and establishment in the target geographic area.

Surveys in the native range

A key part of weed biological control is the study of natural enemies in the native range of the weed. Important issues include determining the native range and origins of an invasive weed population, sites at which to record data, quantitative and systematic methods for native range surveys, identifying natural enemies and studying the impact of the natural enemies of the weed (Goolsby et al. 2006). All these topics are relevant for assessing the risk of herbivores and pathogens in one geographic area on indigenous plants from another geographic area. Knowledge of the native geographic range and host range of the pathogen or herbivore and the variability of the species is needed in order to assess the potential threat from the populations found attacking indigenous plant species outside their home range.

Literature

Published information describing arthropods and pathogens that attack a target weed can help prioritise agent selection. For example, *Lochmaea suturalis* Thomas 1866 (Coleoptera: Chrysomelidae) is considered a pest of heather in Europe, where heather is native and managed for grouse production, so this beetle was the obvious choice for the new biocontrol program against this weed that started in New Zealand in the 1990s (Syrett et al. 2000). For the biological control program against Scotch broom, existing ecological studies (Waloff and Richards 1977) considered aphids, psyllids, *Leucoptera spartifoliella* (Hübner 1813) (Lepidoptera: Lyonetiidae)

Table 2 Threat classification for New Zealand plants (Molloy et al. 2002) and numbers of plant species in some categories (Hitchmough et al. 2007)

Threat classification	Criteria	Number of vascular plant taxa (2004)
Acutely threatened: nationally critical	Very small population or a very high predicted decline	85
Acutely threatened: nationally endangered	A: Small population and moderate to high recent or predicted decline	67
	B: Small to moderate population and high recent or predicted decline	
Acutely threatened: nationally vulnerable	Small to moderate population and moderate recent or predicted decline	23
Chronically threatened: serious decline	A. Moderate to large population and moderate to large predicted decline	29
	B. Small to moderate population and small to moderate predicted decline	
Chronically threatened: gradual decline	Moderate to large population and small to moderate decline	79
At risk: range restricted		445
At risk: Sparse		140

Table 3 Hypothetical examples of different levels of damage that a pathogen or herbivore could cause to a plant organ and the suggested possible impact of different levels of damage to that plant organ

Plant part	Unlikely to reduce vigour of healthy plants or reduce populations	Likely to weaken plants and reduce recruitment	May cause death or occasional reduction in plant populations	Likely to cause loss of populations from at least part of their geographic range
Leaves	Loss of some leaves every year	Occasional partial defoliation	Occasional heavy defoliation	Heavy sustained defoliation
Flowers	Damage to 5% of flower buds	Occasional loss of 50% of flowers	At least 75% of flowers not opening each year	Very few flowers opening
Fruit	10% of fruit partly eaten	Loss of up to 50% of seeds	Loss of at least 95% of seed each year	Almost total seed loss each year
Stems	0.5% of shoots wilting	10% of stems damaged every year	50% of stems girdled and killed most years	Stems of pre-flowing plants killed
Roots	5% of fine roots chewed	Up to 50% of small roots eaten once a year	Damage occasionally kills main tap root	Heavy sustained damage to roots

The impact of a particular level of injury will depend upon plant species biology

and *Phytodecta* (*Gonioctena*) *olivacea* (Forster, 1771) (Coleoptera, Chrysomeloidea) to be the most damaging insects attacking the plant in the UK.

Field surveys

Information regarding the natural enemies of a weed may be insufficient to identify candidate agents and field surveys in the native range are then required. If field surveys need to be conducted, appropriate data should be collected from field sites about localities, especially if there is a soil-dwelling stage. Data from localities in other geographic areas where the indigenous plant has been attacked should be compared with information about the environment in the indigenous ecosystem of the plant. For weed biological control agent surveys, it is recommended that site and sampling data be held in a relational database to facilitate subsequent analysis of survey data (Goolsby et al. 2006), for example to identify specialist species that are commonly associated with a host plant versus generalist species that utilise a plant only intermittently (Palmer and Pullen 1995). Unique surveying and sampling requirements are required for each plant species and herbivore/pathogen combination. Therefore, once a target weed natural enemy has been identified, quantitative survey methods to assess its abundance, seasonal activity and damaging effects on plants should be designed to suit the herbivore/pathogen and the plant species. These surveys can help infer the likely distribution, abundance and possible impacts of potential weed biological control agents within the release environment (Goolsby et al. 2006). We believe that this is also a good approach for risk organisms to indigenous plants in their home range.

Definition of taxa

As with weed biological control projects, herbivores/pathogens found on plants growing in outside their home range, may not be well known taxonomically. In this case it may be useful to combine molecular methods with classical taxonomy to define the species and populations involved. It would be useful to have information about the genetic variability of both the indigenous plant and the herbivore/pathogen because some indigenous non-endemic plants have an extensive natural geographic range and sufficient genetic variability for subspecies to be recognised, e.g. *Dodonaea viscosa* Jacq. (Sapindaceae) (Germplasm Resources Information Network for plants 2007). Herbivore species have been found on some plant subspecies, but not on others e.g. (Kolesik 1995). Similarly, some herbivores are polyphagous and have host strains, races, biotypes or subspecies, e.g. *Heliothis armigera conferta* Walker, 1857 (Lepidoptera: Noctuidae) and kowhai moth, *Uresiphita polygonalis maorialis* (Felder and Rogenhofer, 1875) (Lepidoptera: Pyralidae) (Dugdale 1988). Endemic plants may also be genetically diverse, and plants used in gardens in other countries may be from a narrow genetic base, such as ‘red New Zealand cabbage trees’ [*Cordyline australis* (G.Forst.) Endl. (Agavaceae)] compared to the wild green plants, and these garden types may be more or less susceptible to herbivores/pathogens in other countries than ‘wild’ types of the plants growing in indigenous ecosystems.

Host range of herbivore/pathogen

One aspect of study is host range. For weed biological control, a narrow control agent host-range (monophagy) is often necessary to reduce the risk of it attacking non-target plants (e.g. Louda et al. 2003). However, monophagous herbivores and pathogens are unlikely to be a risk to endemic plants in their indigenous ecosystems, though they may pose a risk to non-endemic indigenous species. Oligophagy or polyphagy are more significant as these organisms are more likely to be pre-adapted to ‘new’ host plants if they establish in a new geographic area. A preliminary analysis of adventive herbivores in New Zealand shows that about 60% of the adventive herbivores that live on New Zealand indigenous plants are polyphagous, compared to 33% of all adventive herbivores found in New Zealand. Studies in other geographic areas can provide information about the timing of herbivore/pathogen activity in relation to the phenology of host plants that could be used to predict the likely severity of damage.

Natural enemies of herbivore/pathogen

Natural enemies in the home range of a herbivore or pathogen may reduce the impact of that herbivore or pathogen on a plant from one geographic area growing in another geographic area, but when ‘released’ from this constraint in the plants indigenous ecosystem, it may cause more damage to the indigenous plant. However, some natural enemies of herbivores in the indigenous ecosystem may have the ability to switch to newly arrived herbivores species, e.g. hymenopterous parasitoids of indigenous leaf miners attack *Phytomyza vitalbae* Kaltenbach 1874 (Diptera: Agromyzidae)—a leaf miner introduced into New Zealand to control *Clematis vitalba* L. (Ranunculaceae) (Paynter et al. 2008)—or the herbivore may even arrive with its natural enemies, e.g. ash whitefly [*Siphonius phillyreae* (Halliday, 1835) (Hemiptera: Aleyrodidae)] (Froud et al. 1998). Thus, the impact of a new herbivore may sometimes be reduced by competing natural enemies in the plants indigenous ecosystem.

Impact of herbivores/pathogens in plants indigenous ecosystem

The impact of herbivores/pathogens on indigenous plants when they are growing in other geographic areas needs to be measured and related to the abundance of the organism in its home range, and its projected abundance in the plants indigenous ecosystem. Generally, in weed biological control programmes, the aim has been to assess the potential impact of a natural enemy on the target weed in its invasive range where it has few or no natural enemies. In contrast, the indigenous plant will be in its home range where it has a suite of natural enemies to which the new pathogen/herbivore adds additional injury. On the other hand the existing suite of natural enemies may compete with and limit the impact of a novel herbivore. In the field of weed biological control, it is generally thought that the chance of finding useful natural enemies for a native weed is lower than for exotic weeds because native weeds may have a saturated community of specialist insects occupying most plants’ niches (Pemberton 2002). Despite this and concerns regarding the desirability of targeting native weeds (e.g. Pemberton 1985), a few classical weed biological control programmes have, nevertheless, targeted native weeds in the past: two of these programmes failed because the agents apparently did not establish. In New Zealand, a sawfly from Chile *Antholcus varinervis* (Spin.), now *Ucona acaenae* Smith, was introduced in 1936 to control the native plant *Acaena anserinifolia* Bur., (Rosaceae) but it did not persist (Valentine 1970). Further, an Argentine weevil (*Heilipodus ventralis* Kuschel) was released against two native *Gutierrezia* spp. (Asteraceae) in New Mexico and Texas in 1988, but establishment of the weevil was not confirmed (Julien 1992). However, biological control of native *Opuntia* species (Cactaceae) by the moth *Cactoblastis cactorum* Berg 1885 (Lepidoptera: Pyralidae) was successful on Santa Cruz Island, just off the California coast (Goeden et al. 1967) and in the Caribbean Island of Nevis (Simmonds and Bennett 1966), from whence *C. cactorum* spread to Florida where it attacks all six native *Opuntia* species and one of the rare species, *Opuntia spinosissima* P. Miller, which is now threatened with extinction (Johnson and Stiling 1998). These cases demonstrate that the effect of introducing an additional herbivore/pathogen to control a native host plant is even more difficult to predict than the effect of introducing a single herbivore/pathogen to control a natural host plant species in a novel environment. Nevertheless, the example of *Opuntia spinisissima* in Florida demonstrates that the extra stress of a novel natural enemy may tip the balance towards extinction of a threatened species.

Plant demography and response to disease/herbivory

In weed biological control an important aspect of natural enemy selection is based on understanding plant demographics and responses to herbivores/pathogens (Raghu et al. 2006). The authors suggest a three-step process (Fig. 2). In step 1, they suggest that matrix models are a suitable tool for identifying the vulnerable stages in plant life cycles (Figs. 3, 4). This appears to be a useful approach for assessing the risk to indigenous plants in their indigenous ecosystems.

Step 2 investigates the plant response to herbivores/pathogens and considers if it is possible to establish *a priori* the plant response to different kinds

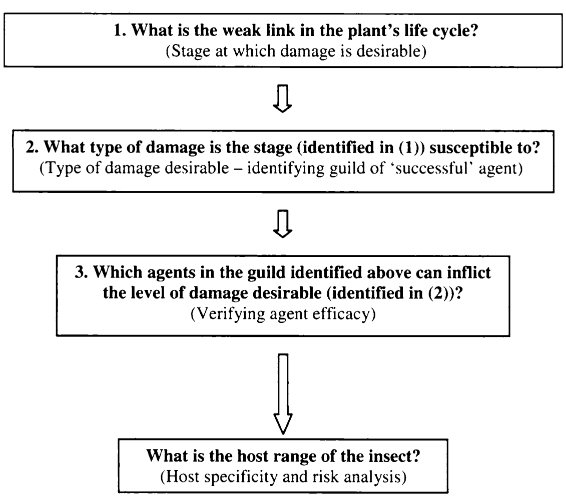

Fig. 2 Nested filters in agent selection process based on plant (weed) ecology (from Raghu et al. 2006, Fig. 1, p. 309)

of herbivores/pathogens. Simulating plant damage, e.g. artificial defoliation, is one approach that has been attempted. The advantages of simulated herbivory experiments include the ability to control for type, intensity and frequency of the damage, while simultaneously controlling other confounding effects (Raghu et al. 2006). For example, in weed biological control it is important to separate the potential impact of a candidate biological control agent from other natural enemies on the target plant. Raghu et al. (2006) list several examples where simulated herbivory produced comparable impacts to actual herbivory measured in the field. However, the use of simulated herbivory in ecological research has been the subject of debate and, although simulated herbivory may provide valuable clues about plant compensation or tolerance of damage, inferences on more complex ecological interactions are likely to be flawed (Hjalten 2004, cited in Raghu et al. 2006). Thus, while it may be possible to accurately simulate the impact of a single new herbivore/pathogen on an indigenous plant, it may prove impossible to realistically simulate the combined impact of indigenous natural enemies in combination with the additional stress of a novel disease/herbivore. Furthermore, although generally considered suitable to leaf-feeders, simulated herbivory does not take into account toxic insect saliva and is not suitable for gall formers and other endogenous feeders (Raghu et al. 2006). Finally, in order to conduct meaningful experiments there is a need for relevant information on the ecology of indigenous plants, such as the native and adventive natural enemies that are already present that may not be well documented.

As part of studies on potential weed biological control agents, it was found useful to identify the number and kinds of herbivores that damaged the different plant organs (Briese 2006). This information is also important for threatened indigenous plants because the severity of damage to different plant organs can affect the survival and reproductive potential of the plant (Table 3). Some herbivore-plant databases include information about the plant organs damaged and the kinds of damage caused to plants e.g. Australian Biological Resources Study (Online resources) www.environment.gov.au/biodiversity/abrs/online-resources/fauna/index.html and Plant-SyNZ database (NA Martin unpublished information). However, these database do not include

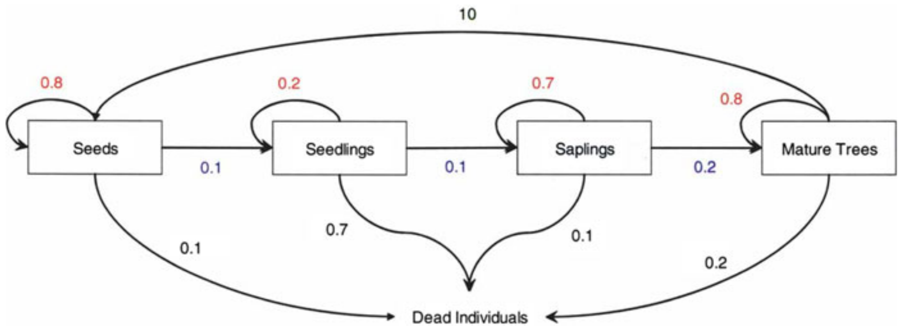

Fig. 3 An illustration of the components of a matrix model using a hypothetical tree. The numbers adjacent to the arrows are the probability of an individual moving from one stage to the next. Because individuals survive, grow or die, the probabilities from each stage add up to 1 (except for reproducing individuals where one tree produces many seeds, for example 10) (from Raghu et al. 2006, Fig. 2)

	Seeds	Seedlings	Saplings	Mature trees
Seeds	0.8	0	0	10
Seedlings	0.1	0.2	0	0
Saplings	0	0.1	0.7	0
Mature trees	0	0	0.2	0.8

Fig. 4 A transition matrix for the hypothetical tree in Fig. 3. The elements are colour-coded to match Fig. 3 (*red* indicates survival rates, *blue* indicates development rates, *green* indicates reproduction) (from Raghu et al. 2006, Fig. 3)

information on the levels of damage found nor the impact of this level of damage. These two kinds of information require special observations and experiments, and from observations in New Zealand indigenous ecosystems and other habitats, the levels of damage from a particular herbivore can be very variable spatially and temporally (Martin unpublished information).

Step 3 attempts to verify herbivore/pathogen efficacy for weed control by determining whether the natural enemy will cause the desired level of damage and whether it will reach the necessary population density to achieve this level of damage. The effects of the herbivore/pathogen on the indigenous plant can be measured in other geographic areas where high infestations occur or can be induced. Subsequently, the impact of the level of damage, in combination with existing herbivores/pathogens, can be simulated for conditions in the indigenous geographic area, for example, using plant demography models. Louda et al. (2005), for example, used plant demography models to assess non-target effects of weed biocontrol agents.

An aim of weed biological control research is to predict the expected population dynamics of the biological control agent. While detailed modelling is not usually feasible, it is possible to use a mechanistic climate-modelling approach where it is assumed that climate is the main limiting factor (Zalucki and van Klinken 2006). This kind of modelling can be assisted and improved by collecting appropriate data (e.g. the geographical distribution of an agent, the number of generations each year, whether the agent has a diapause stage and, if so, what conditions initiate diapause) during the quarantine testing phase and from surveys in other countries. The CLIMEX model is recommended for such population dynamic studies (Zalucki and van Klinken 2006) and the strengths and limitations of CLIMEX are described by Sutherst (2003). Zalucki and van Klinken (2006) outline the kinds of basic information required and discuss the need to consider other factors such as synchrony with host plant, host plant quality, habitat differences and potential impact of natural enemies in the new environment. All these are relevant for predicting the impact of adventive herbivores/pathogens on plants indigenous to other geographic areas.

There are many papers on the impact of invasive herbivores on crops, but few such studies on their impact on indigenous plants in the new geographic area. Can we learn anything from predictions of invasions and subsequent establishment of herbivores/pathogens in crops in a new area that may be applicable to what might happen with indigenous plants? A considerable amount of information is available about the host plants of a recent invader into

New Zealand, *Bactericera cockerelli* (Sulc, 1909) (Hemiptera: Triozidae), which originates in North America where it breeds outdoors on Solanaceae and Convolvulaceae (Wallis 1955). Host plants include several species of *Solanum* including *S. nigrum* L., a common weed in New Zealand. A New Zealand indigenous plant, *S. aviculare* is listed as a plant on which adult psyllids had been found. On the basis of the published information, it could be a host plant for *B. cockerellii*. The psyllid has been found breeding on *S. aviculare* G.Forst. in New Zealand, but it is does not appear to be a favoured host, with only low numbers of nymphs present on some leaves (Martin 2008). This supports the view that predictions of risk can be made. However, while this psyllid has been found breeding on the known crop plants, and several known Solanaceae weed hosts, it has not been found breeding on *S. nigrum*. This suggests that caution should be used when interpreting published host associations from other countries data, especially where there are no details about the relative breeding success of the herbivore on a host plant or where there could be different biotypes of the plant or herbivore/pathogen.

Number of propagules needed for establishment

Another challenge for classical biological control is the number of propagules that need to be released to establish the biological control agent. When assessing the risk of a herbivore/pathogen establishing in a new geographic area, the greater the number of propagules required for successful establishment, the lower the risk of establishment (Brockerhoff et al. 2006; Grevstad 1999; Memmott et al. 2005). Timing of dispersal behaviour can be an important factor affecting the size of inoculum required, e.g. the failure to establish by three species of tephritid fly released in Australia for control of *Onopordum* spp. thistles was believed to be partly due to adult flies having a dispersal phase before mating (Briese 2006, pp. 321–322). Several biological parameters that could affect successful establishment of adventive herbivores were assessed by Peacock and Worner (2008) who found that herbivores with a lower development threshold temperature were more likely to establish in New Zealand than species with a higher developmental threshold.

Discussion

In weed biological control many of the recommended processes for studying herbivore/pathogen host associations are relevant for studies of the risk to indigenous plants in their indigenous ecosystems by herbivores/pathogens from another geographic area. These include setting clear objectives at the start of the project and studies in the native range of the herbivore/pathogen, including quantitative studies (herbivore/pathogen and host plant indigenous to another geographic area). Good knowledge of the ecology of the host plant (weed or indigenous plant) is also important. Where necessary, there should be taxonomic studies (including the use of molecular techniques) on the plant and the herbivore/pathogen. It is also necessary to understand the demography of the plant, its response to herbivory/disease, and determine plant population dynamics through modelling the impact of climate.

However, there are some significant differences of approach from weed biological control when studying the potential impact of adventive herbivores/pathogens on indigenous plants. When determining desired outcomes, the threat classification of the indigenous plant is important when deciding on priorities; for example, is a Nationally Critical species of higher priority than a Gradual Decline species (Table 2)? Other criteria could include dominance in ecosystems, importance in ecosystem functioning, economic value and importance to the indigenous people of the plants native area. Weed biological control researchers are usually searching for monophagous or oligophagous natural enemies. However, when studying the risk to indigenous plants, polyphagous herbivores/pathogens are likely to be of more interest/concern as they are more likely to be 'pre-adapted' to new host plants. Weed biological control researchers usually only study the impact of the natural enemy on its own or in combination with a limited number of other natural enemies, whereas when studying the risk to indigenous plants the combined impact of the new herbivore/pathogen needs to be assessed in combination with a suite of existing natural enemies and any other unanticipated host plants.

Knowledge of the host range of a potentially invasive herbivore/pathogen is critical for assessing the risk of establishment and threat to indigenous plant species. The greater the number and abundance of potential host plants (indigenous, naturalised or cultivated) the greater the chance of establishment. Also if the 'new' herbivore/pathogen could survive/multiply on more than one host plant species in the plants indigenous ecosystems, 'apparent competition' could put one of the host plants at greater risk than others (Holt 1977; Morris et al. 2004). The concept of apparent competition is usually applied to predators or parasitoids and their prey or hosts respectively, but seems equally applicable to herbivores and pathogens and their host plants. In this scenario, a herbivore could survive on a common, but less favoured host, and be present to attack a more favoured and vulnerable indigenous host plant. For example, the Australian possum [*Trichosurus vulpecula* (Kerr, 1792) (Mammalia: Phalangeridae)] that was released and established in New Zealand feeds on a wide range of trees and shrubs, but through preferential feeding threatens the survival of less common species such as mistletoe in native beech forests (www.landcareresearch.co.nz/publications/infosheets/possums/possum_native_vege.pdf (accessed July 2008)). Similarly an exotic leaf mining fly, *Chromatomyia syngenesiae* Hardy 1849 Diptera: Agromyzidae) lives on naturalised and indigenous *Senecio* species (Asteraceae) in New Zealand and can reach high densities on some naturalised and indigenous species. If populations were not subject to high parasitism in summer (NA Martin unpublished data), some rare annual or biennial indigenous *Senecio* species might be at high risk from reservoirs of flies on other *Senecio* species.

Indigenous plants can be put at risk by herbivores and pathogens from other geographic areas. For example two trees, English elm (*Ulmus procera* Salisb. Ulmaceae) in the British Isles and American chestnut (*Castanea dentata* (Marsh.) Borkh. Fagaceae) in North America, have been prevented from forming full-sized trees by two fungal pathogens, *Ophiostoma novo-ulmi* Brasier 1991 (Brasier 1996) and *Cryphonectria parasitica* (Murr.) Barr (Wikipedia 2007), respectively. No New Zealand indigenous plants appear to be at high risk from any adventives invertebrate herbivores already in the country, though two species could have put plant species at risk if they were not controlled by natural enemies—*Senecio* species by a leaf mining fly, *C. syngenesiae* (see above) and *Leptospermum scoparium* J.R. et G. Forst. (Myrtaceae) by the felted scale, *Eriococcus orariensis* Hoy 1954 (Hemiptera: Eriococcidae), which was controlled by a fungal pathogen (Hoy 1961, van Epenhuijsen et al. 2000).

Risk assessment procedures will require good knowledge of the ecology of indigenous plants and their herbivores and pathogens so that the impact of additional herbivores/pathogens can be gauged. In New Zealand information about the herbivores associated with plants and details of the damage they cause to host plants is being assembled in the Plant-SyNZ database. Knowledge of the microclimates occupied by each plant species is required because habitats such as damp forest, gullies or alpine herb fields are likely to be very different from botanic gardens in other countries where many plants from other geographic regions are grown. The ecological structure of a botanic garden is likely to be more similar to botanic gardens and suburbs in the plants indigenous geographic area rather than to the indigenous ecosystems of the plant species. The ability to predict infestations of adventive herbivores/pathogens on indigenous plants in their indigenous ecosystems from observations in botanic gardens could be tested by comparing the distribution of adventive species in the plants indigenous geographic area, i.e. which species infest plants in urban areas and which extend into the indigenous ecosystems.

In order to make a well informed assessment of the suitability and safety of a potential weed biological control agent or the risk from a foreign herbivore/pathogen to an indigenous plant, good quality information derived from detailed research is required. For weed biological control this focuses on a few target weeds and a small number of herbivores/pathogens and in classical weed biological control the first step is to determine the target weed (Fig. 1). The factors important for selecting target weeds on conservation land are discussed by Syrett (2001) and information required for selection potential biological control agents are summarised in this paper. In contrast, the assessment of risk from a foreign herbivore/pathogen to an indigenous plant in its home range is less focused with many potential host plants and many herbivores/pathogens requiring consideration. Fifty-one such herbivores are listed in the Plant-SyNZ database (2009). It is thus unlikely to be practical to undertake the detailed research required for a full assessment of risk to indigenous plants from all the herbivores/pathogens in other geographic areas that are found to infest them. It would be useful to have a pre-screening procedure to prioritise the herbivores/pathogens and to test simplified data requirements for risk assessments.

For organisms associated with imported crops that might threaten crop plants, biosecurity organizations such as the Ministry of Agriculture and Fisheries Biosecurity New Zealand have a pre-screening procedure for deciding if a full risk assessment is justified (Anonymous 2006). A similar pre-screening process could be used to decide which indigenous plant species and which herbivores/pathogens found to infest them in other countries should be examined thoroughly and subject to detailed research. Plant threat status (Table 2), the part of a plant damaged and the severity of damage (Table 3) could form the basis of guidelines. Other factors in the pre-screening guidelines could include importance of a plant in key ecosystems, such as *Nothofagus* species in New Zealand beech forest, simplified climate matching based on known distributions, and estimates of the impact on host plants based on similar herbivore/pathogens. These guidelines could be checked by comparing information known about an adventive herbivore/pathogen established in the indigenous plants home range and comparing predicted severity of damage with the distribution and severity of actual attack on the plant in its home range. The adventive herbivores in New Zealand provide a suitable resource for such studies. About 145 adventive herbivores in New Zealand are known to attack New Zealand indigenous plants (unpublished information) of which good quality host association information is available for 128 species (Table 1).

Conclusions

Methods and approaches used in classical biological control of weeds to select potential biological control agents form a useful framework for assessing the risk of herbivores/pathogens in other countries to indigenous plants in their indigenous ecosystems. These include having clear outcomes, studies in the environment in other countries, good knowledge of the ecology of the plant, taxonomic studies of the host plant and herbivore/pathogen, and modelling of their interactions in a new environment. Key differences in emphasis for studies on risk to indigenous plants include a strong interest in polyphagous species and potential interactions with the existing natural enemies of the indigenous plants.

A key challenge will be devising criteria to be used to decide on priorities for conducting risk assessments on herbivores/pathogens in other geographic areas that are found attacking indigenous plants in their home range. The methodologies developed to assess the risk to indigenous plants can then be tested by comparing the outcomes of such an analysis on an adventive species already in the plants indigenous geographic area with its impact on the plant species in its indigenous ecosystems.

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References

Anonymous (2006) Biosecurity New Zealand risk analysis procedures, version 1. Ministry of Forestry and Agriculture Biosecurity New Zealand, Wellington, 103 p

Brasier CM (1996) New horizons in Dutch elm disease control. Report on Forest Research, 1996. Forestry Commission, HMSO, London, pp 20–28

Briese DT (2006) Can an *a priori* strategy be developed for biological control? The case of *Onopordum* spp. Thistles in Australia. Aust J Entom 45:317–323

Brockerhoff EG, Bain J, Kimberley M, Knízek M (2006) Interception frequency of exotic bark and ambrosia beetles (Coleoptera: Scolytinae) and relationship with establishment in New Zealand and worldwide. Can J For Res 36(2):289–298

Crop Protection Compendium (2004) CD ROM edition. CAB International, Wallingford

Dugdale JS (1988) Lepidoptera—annotated catalogue, and keys to family-group taxa. Fauna NZ 14:1–282

Froud KJ, Charles JG, Allan DJ (1998) Tree pests: some recent arrivals in New Zealand. (poster abstract). In: Proceedings of New Zealand Plant Protection Conference vol 51, p 267

Germplasm Resources Information Network - (GRIN) [Online Database] (2007) USDA, ARS, National Genetic Resources Program. National Germplasm Resources Laboratory, Beltsville, Maryland.URL: www.ars-grin.gov/cgi-bin/npgs/html/taxon.pl?14441 (24 October 2007)

Goeden RD, Fleschner CA, Ricker DW (1967) Biological control of prickly pear cacti on Santa Cruz Island, California. Hilgardia 38:579–606

Goolsby JA, van Klinken RD, Palmer WA (2006) Maximising the contribution of native-range studies towards the identification and prioritisation of weed biocontrol agents. Aust J Entomol 45:276–286

Grevstad FS (1999) Experimental invasions using biological control introductions: the influence of release size on the chance of population establishment. Biol Invasions 1(4):313–323

Hitchmough R, Bull L, Cromarty P (comps) (2007) New Zealand threat classification system lists—2005. Department of Conservation, Wellington, 194 p

Holt RD (1977) Predation, apparent competition and the structure of prey communities. Theor Popul Biol 12:197–229

Hoy JM (1961) *Eriococcus orariensis* Hoy and other Coccoidea (Homoptera) associated with *Leptospermum* Forst. Species in New Zealand. Department of Scientific and Industrial Research (DSIR) Bulletin 141

IPPC (2005) Identification of risks and management of invasive alien species using the IPPC framework. In: Proceedings of workshop in Braunschweig, Germany 22–26 September 2003. International Plant Protection Convention Secretariat, FAO, Rome, Italy

Johnson DM, Stiling PD (1998) Distribution and dispersal of *Cactoblastis cactorum* (Lepidoptera: Pyralidae), an exotic *Opuntia*-feeding moth, in Florida. Florida Entomol 81:12–22

Julien MH (1992) Biological control of weeds: a world catalogue of agents and their target weeds, 3rd edn. CAB International, Wallingford, p 186

Kolesik P (1995) *Asphondylia dodonaeae*, a new species of Cecidomyiidae (Diptera) damaging leaves and branches of hop-bush, *Dodonaea viscosa* (Sapindaceae) in Australia. Trans Royal Soc South Aust 119(4):171–176

Louda SM, Pemberton RW, Johnson MT, Follett PA (2003) Non-target effects: the Achilles heel of biological control? Retrospective analyses to reduce risk associated with biocontrol introductions. Ann Rev Entomol 48:365–396

Louda SM, Rand TA, Arnett AE, McClay A, Shea K, McEachern AK (2005) Evaluation of ecological risk to populations of a threatened plant from an invasive biocontrol insect. Ecol Appl 15:234–249

Martin NA (2008) Host plants of the potato/tomato psyllid: a cautionary tale. Weta 35:12–16

Memmott J, Craze PG, Harmman HM, Syrett P (2005) The effect of propagule size on the invasion of an alien insect. J Animal Ecol 74:50–62

Molloy J, Bell B, Clout M, de Lange P, Gibbs G, Given D, Norton D, Smith N, Stephens T (2002) Classifying species according to threat of extinction. A system for New Zealand. Threatened species occasional publication 22. 26 p

Morin L, Evans KJ, Sheppard AW (2006) Selection of pathogen agents in weed biological control: critical issues and peculiarities in relation to arthropod agents. Aust J Entomol 45:349–365

Morris RJ, Lewis OT, Godfray HCJ (2004) Experimental evidence for apparent competition in a tropical forest food web. Nature (London) 428:310–313

Palmer WA, Pullen KR (1995) The phytophagous arthropods associated with *Lantana camara*, *L. hirsuta, L. urticifolia* and *L. urticoides* (Verbenaceae) in North America. Biol Control 5:54–72

Paynter Q, Martin N, Berry J, Hona S, Peterson P, Gourlay AH, Wilson-Davey J, Smith L, Winks C, Fowler SV (2008) Non-target impacts of *Phytomyza vitalbae* a biological control agent of the European weed *Clematis vitalba* in New Zealand. Biol Control 44:248–258

Peacock L, Worner SP (2008) Biological and ecological traits that assist establishment of alien invasive insects. NZ Plant Prot 61:1–7

Pemberton RW (1985) Native weeds as candidates for biological control research. In: Delfosse ES (ed) Proceedings of the VI international symposium on biological control of weeds. Ottawa, Canada, Agriculture Canada, pp 869–877

Pemberton RW (2002) Selection of appropriate future target weeds for biological control In: Van Driesche R et al (eds) Biological control of invasive plants in the eastern United States. Morgantown WV, USDA Forest Service Publication FHTET-2002-04, pp 375–386

Plant-SyNZ database (2009) www.crop.cri.nz/home/plant-synz/index.php (Accessed February 2009)

Raghu S, van Klinken RD (2006) Refining the ecological basis for agent selection in weed biological control. Aust J Entomol 45:251–252

Raghu S, Wilson JR, Dhileepan K (2006) Refining the process of agent selection through understanding plant demography and plant response to herbivory. Aust J Entomol 45:308–316

Simmonds FJ, Bennett FD (1966) Biological control of Opuntia spp. by *Cactoblastis cactorum* in the Leeward Islands (West Indies). Entomophaga 11:183–189

Sumner DA (ed) (2003) *Exotic pests and diseases: biology and economics for biosecurity*. Iowa State Press, Ames. 265 pp

Sutherst RW (2003) Prediction of species geographical ranges. A critical comment on M.J. Samways, R. Osburn, H. Hastings and V. Hattingh (1999) Global climate change and accuracy of predictions of species geographical ranges: establishment of introduced ladybirds (Coccinellidae, *Chilocorus* spp.) worldwide. J Biogeography 26, 795–812. J Biogeography 30: 805–816

Syrett P (2001) Biological control of weeds on conservation land: priorities for the Department of Conservation. Landcare research contract report: LC0102/038. 29 p

Syrett P, Smith LA, Bourner TC, Fowler SV, Wilcox A (2000) A European pest to control a New Zealand weed: investigating the safety of heather beetle, *Lochmaea suturalis* (Coleoptera: Chrysomelidae) for biological control of heather, *Calluna vulgaris*. Bull Entomol R 90:169–178

Valentine EW (1970) A list of the phytophagous hymenoptera in New Zealand. NZ Entomol 4(4):52–62

van Epenhuijsen CW, Henderson RC, Carpenter A, Burge GK (2000) The rise and fall of manuka blight scale: a review of the distribution of *Eriococcus orariensis* (Hemiptera: Eriococcidae) in New Zealand. NZ J Entomol 233:67–70

van Klinken RD, Raghu S (2006) A scientific approach to agent selection. Aust J Entomol 45:253–258

Waage JK, Mumford JD (2008) Agricultural biosecurity. Phil Trans R Soc B 363:863–876

Wallis RL (1955) Ecological studies on the potato psyllid as a pest of potatoes. Tech Bull US Dep Agric 1107:1–25

Waloff N, Richards OW (1977) The effect of insect fauna on growth, mortality and natality of broom, *Sarothamnus scoparius*. J Appl Ecol 14:787–798

Wikipedia (2007) http://en.wikipedia.org/wiki/Chestnut_blight (20 November 2007)

Zalucki MP, van Klinken RD (2006) Predicting population dynamics of weed biological control agents: science or crystal balls? Aust J Entomol 45:331–344