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REVIEW

Encompassing the relative non-target risks from agents and their alien plant targets in biological control assessments

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Abstract Criticisms about the safety of biological control of alien plants has resulted in a risk-averse approach, where the risks posed by the agent are paramount and the risks posed by the alien plant are neglected. We argue that the risk associated with non-target damage from agents needs to be assessed relative to that of their target alien plants. A literature review of the non-target risks associated with biological control agents was undertaken in terms of the risk to native species from agents relative to the risk to native species from their alien plant targets. We then developed a framework that compares the consequence with the likelihood of non-target damage for both agents and their targets to provide an overall risk rating. Assessments of the risk of damage from both agents and their target alien plants will enable researchers, managers and policy makers to better assess the risks from biological control.

Keywords Non-target effects · Likelihood · Consequence · Framework · Risk-averse

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Introduction

Alien plant species are a significant global problem (Pimentel 2002). Thus considerable effort has been directed towards their control and management. One such control measure, classical weed biological control (biological control hereafter), uses the alien plant's natural enemies as the method of control (van den Bosch and Messenger 1973). Biological control has been used for > 140 years to control alien plants (McFadyen 1998; Moran and Hoffmann 2015), and has been shown to be a cost-effective control technique (Fowler et al. 2000), based on both current benefit-cost analysis (Page and Lacey 2006) as well as estimated future benefits (van Wilgen et al. 2004).

Whilst there are significant benefits from the biological control of alien plants, there have been some undesirable outcomes, which have resulted in some major criticisms of the science (e.g. Howarth 1991; Simberloff and Stiling 1996a, b). The basis of most criticism is that some agents pose non-target effects (Simberloff and Stiling 1996a; Fowler et al. 2000; Pemberton 2000; Willis et al. 2003). Some of the published criticisms about the risks associated with biological control of alien plants may be misleading in that they stem from atypical introduction histories (for example, agents that were not intentionally introduced into the area where negative impacts have been recorded, and agents that were released at a time when the predicted non-target effects were deemed less important than they are today) (Delfosse 2005; Fowler et al. 2000; Moran and Hoffmann 2015). The biological control of alien plants has a significantly better track record than programs for alien insects and alien vertebrate pests (Simberloff and Stiling 1996a). Several iconic 'failures' [e.g. cane toads (*Bufo marinus*) in Australia (Freeland 1986)] and some significant non-target effects [i.e. to native thistles in the USA from *Rhinocyllus conicus* (Delfosse 2005)], combined with the need to allay public fears of damage to economically useful plants (Huffaker 1957), has seen the regulators of biological control of alien plants adopt a risk-averse or precautionary approach to the release of agents (Moran and Hoffmann 2015). This risk-averse approach aims to prevent the risk of non-target effects associated with the release of agents (i.e. to a native or commercially valuable species).

The risk-averse position has resulted in the refinement of stringent host-specificity testing (Delfosse 2005), improved test plant selection (Wapshere 1974; Briese 2003) and host-specificity procedures (Wan and Harris 1997; Briese 2005), improved pre-release assessments (Louda et al. 2003), along with stringent legislation, policy and regulations for releasing biological control agents (Sheppard et al. 2003; Klein et al. 2011). Recent assessments of host-specificity testing results have highlighted how the risk could be minimised further. For example, Paynter et al. (2015) found a threshold effect, above which the probability of host use [non-target effects] rose from virtually zero to an almost certainty. Developments such as these have significantly improved the safety record for biological control agents in recent years (Sheppard et al. 2003, 2005; Messing and Wright 2006; Suckling and Sforza 2014).

The adoption of a risk-averse position, however, could have detrimental outcomes, in that it may limit the release of effective agents, which pose only minor risks (Hinz et al. 2014) or no risks at all (Fowler et al. 2012). The impact of this risk-averse approach is not confined to the direct effect of potentially not controlling an invasive alien plant, as it has broader implications for the science and those who work within it (Moran and Hoffmann 2015).

Ironically despite the risk-averse position adopted, numerous agents have been released notwithstanding non-target effects being identified during host-specificity testing, some of which have subsequently resulted in minor non-target damage (see Willis et al. 2003) illustrating significant inconsistencies in the level of risk which is deemed acceptable and how risk is applied in the decision and approval making processes. Such inconsistencies are associated with the way in which the perceived risk is evaluated against the perceived benefits of biological control agents. Typically, the greater the perceived benefits, the higher the level of acceptable risk that decision makers are prepared to accept (Delfosse 2005). Thus decisions to release biological control agents must encompass both benefits and a range of risks (Sheppard et al. 2003; Jetter 2005).

Changes in societal values have also affected how biological control programs have been perceived as well as the degree of risk that is deemed acceptable (Delfosse 2005). For example, native thistles were considered of little value when the decision to release *R. conicus* was made in the late 1960s. However, changes in societal values have subsequently led to increased value being put on native species, including thistles, during the intervening 40+ years. As predicted by pre-release host specificity tests, *R. conicus* went on to attack native thistles (Zwölfer and Harris 1984). The initial decision to release *R. conicus* is now being retrospectively judged with today's values, despite the risk being deemed acceptable at the time of the release (Delfosse 2005; Suckling and Sforza 2014). Given the impossibility of predicting future changes in societal values, current policies and regulations must be underpinned by the latest scientific knowledge that builds on previous lessons, combined with robust documentation.

Whilst the introduction of biological control agents presents a potential risk to non-target species, this is however not the only associated risk. There are risks associated with doing nothing, in that alien plants may continue to threaten native species in the absence of effective control. Whilst not always explicitly stated, the risk of doing nothing is often incorporated as a way of determining the benefit (McFadyen et al. 2002; Willis et al. 2003) and by default the target risk. The use of counterfactuals (i.e. if control had not been implemented) to determine the benefits of controlling biological invasions have not, until recently, been used (see McConnachie et al. 2016), including for biological control.

Despite several authors outlining the need to better document and incorporate the negative effects associated with the target alien plants in biological programs (e.g. Moran et al. 2005; Thomas and Reid 2007; Müller-Schärer and Schaffner 2008), no framework on how such information could be used in decision making or risk assessment processes has been proposed, which has led to inconsistencies around the level of risk deemed to be acceptable. Thus assessments that combine all the risks relative to the benefits (including counterfactuals) are needed to determine the net benefit of introducing a biological control agent.

Here we argue that in many instances the risk associated with the impacts from the target plant species on native species is just as important a consideration as the non-target effect associated with a biological control agent. The risk associated with the impact of the target alien invasive plant species should therefore be considered in the assessment process for the release of biological control agents.

Definition of risk

A formal definition of risk is adopted here (i.e. Anon 2006), in which risk is assessed through the combination of the consequences of an event [the risk] and the likelihood of that event occurring.

How risks have been considered in biological control

An assessment of the use of the term 'risk' in the literature associated with non-target effects from alien plant biological control programs showed that the term has been applied inconsistently. In most instances the term risk has been used to describe the perceived or potential risk [i.e. the risk of non-target effects from agents, or the risk of finding suitable agents (Moran et al. 2005)], being simply is there a risk or not. The actual level or degree of risk, however, is rarely described or quantified, and assessments of risk have rarely used a formal risk framework, despite the introduction of risk assessments potentially having significant benefits (Simberloff and Stiling 1996b; Shaw et al. 2011).

The current approach to assessing the 'risks' associated with the release of a biological control agent is not in line with other risk assessment systems used for alien plants, in that a formal risk framework is not used, despite previous attempts to do so and it being a requirement in some release procedures (e.g. Barratt and Moeed 2005; Shaw et al. 2011). Additionally, Sheppard et al. (2005) outlined how a formal risk assessment structure could direct biological control research and thus reduce the risk. Others have outlined the need for a more formalised risk assessment approach (e.g. Delfosse 2005), whilst Shaw et al. (2011) used a formal risk assessment framework to gain approval for the first biological control program for an alien plant in Europe.

There have been several attempts to assess/determine the risk associated with the release of biological control agents for alien plants using approaches that resemble the formal definition of risk outlined above. For example, Lonsdale et al. (2001) outlined a risk framework that comprises an assessment of the exposure to the risk (i.e. likelihood that the agent could cause damage) relative to a response associated with the risk (i.e. level of damage). The framework however is difficult to apply when the nature of the risk is multifaceted, or when data is limited (Smith 2006), both being common problems. Whilst Martin and Paynter (2010) outlined a process for assessing the damage from agents in a risk context, which combines likelihood and consequence, using a series of hypothetical levels of damage to the main plant parts (e.g. leaves, flowers, stems, etc.).

Wright et al. (2005) proposed the use of precision trees to assess risk, in which the probability of a decision is compared with the probability of the opposition decision (i.e. release or not release) based on available data. Jetter (2005) outlined the use of an economic framework in which to evaluate the risks against the benefits. From this purely economic perspective, agents should be released where the benefits outweigh the costs, although it is hard to put values on costs such as non-target effects or loss of biodiversity despite some attempts to do so (e.g. van

Wilgen et al. 2004). Jarvis et al. (2006) demonstrated the value of evaluating the risk with the benefits, in that despite potential non-target damage the benefits outweighed the costs, and the biological control program was allowed to continue. Moreover, Jetter (2005) argued that in instances where target alien plants have high irreversible damage, biological control is needed sooner. None of the formal risk assessments have taken an approach in which both the risk of damage to non-target plants by the biological control agent and the risk of damage to non-target plants from the target alien plant are considered.

Agent risk

Despite documented cases of non-target effects, the incidence of such effects from biological control agents is small and predictable (Pemberton 2000; Suckling and Sforza 2014; Moran and Hoffmann 2015). For example, only 3 % of the agents examined by Funasaki et al. (1988) in Hawaii had non-target effects, none of which were released post 1967. Fowler et al. (2000) suggested that as little as two (0.5 %) of ∼400 agents released worldwide have posed significant non-target damage. A recently published review of non-target impacts of biological control agents for alien plants found only four of 512 agents (0.8 %) had any adverse effect on non-target plant populations, all of which were in the same genus as the target (Suckling and Sforza 2014). Such low instances, however, are not sufficient evidence alone, given the limited effort made to monitor and assess non-target impacts (Simberloff and Stiling 1996a).

The lack of post-release evaluation of non-target effects associated with the release of biological control agents has led to criticisms and suggestions that non-target effects are more common than anticipated (e.g. Simberloff and Stiling 1996a). However, all assessments of non-target effects made in the last 20 years show the reverse (i.e. few examples despite large numbers of agents released) (Fowler et al. 2000; Suckling and Sforza 2014). Although many authors have argued that post-release evaluations must be a priority (e.g. Simberloff and Stiling 1996a, b; Willis et al. 2003; Paynter et al. 2004; Denslow and D'Antonio 2005; Hinz et al. 2014), it is still not a mandatory requirement or routinely undertaken to examine potential off-target effects.

In a dedicated non-target post-release evaluation of 20 biological control agents across New Zealand, Paynter et al. (2004) found 16 (80 %) to be host specific, two (10 %) had very minor non-target damage to native plants (sporadic or rare), which was predicted during host-specificity testing, and two others for which the non-target damage was not predicted, but confined to related alien plant taxa. On closer examination of the host-specificity tests for these agents, Paynter et al. (2004) concluded that for three of four agents that posed non-target damage the host-specificity tests were inadequate and that improved testing would have predicted the effects prior to release. Host specificity tests are today more rigorous than those evaluated by Paynter et al. (2004). The results from host-specificity tests are typically conservative as the level of non-target damage observed may be overstated by the very nature of no-choice testing (Messing and Wright 2006) and the broad range of test plants used (Zwölfer and Harris 1971). Non-target effects can also be density-dependent in that the local density of the target alien plant can determine the level of non-target damage observed to native species (see Rand et al. 2004; Baker and Webber 2008).

Caution should be used when drawing comparisons between the non-target effects of agents which have atypical introduction histories with those that have not. For example, of the ten agents with non-target effects reviewed by Louda et al. (2003), two have atypical introductions. The non-target effects attributed to (i) *Cactoblastis cactorum* only occurred after it arrived in Florida, where it was never released as a deliberate biological control agent and the original releases were made to control a native plant in the Caribbean (Pemberton and Liu 2007), and (ii) *Larinus carlinae* only occurred when it was deliberately distributed following its discovery as an incidental introduction in the USA, its incidental introduction being seen as beneficial at the time. Whilst these two examples highlight the dangers and likely outcomes of introducing new species in an unregulated manner, using them to illustrate the level of non-target effects associated with regulated biological control releases is likely to be misleading given the different introduction processes and level of science, regulation (legislation and policy) and rigidity of host-specificity testing prior to regulated releases. Such examples also contribute to the risk-averse position adopted by regulators.

Retrospective assessments of several biological control agents showed that the current risk-averse position would have prevented the successful release of beneficial agents in New Zealand (Fowler et al. 2012) and the USA (Hinz et al. 2014). All five agents examined by Hinz et al. (2014) would be rejected under current screening processes. Each of these agents have significantly contributed to the control of their respective major invasive alien plant species, with minimal observed non-target effects. The authors concluded that assessments based solely on the risks associated with agents are very likely to lead to missed opportunities. Both Hinz et al. (2014) and Fowler et al. (2012) argue that unless improvements are made to risk assessment processes, potentially successful and safe agents will be rejected due to an excessively risk-averse approach. This is not to say that all rejected agents should be re-evaluated, as some clearly pose a high level of risk (e.g. Syrett and Harman 1995).

Despite a highly risk-averse approach to the release of biological control agents, some agents are paradoxically released even though host-specificity tests indicate the potential for non-target effects (i.e. a predicted non-target risk). A number of these agents subsequently go on to cause non-target damage (Pemberton 2000; Willis et al. 2003; Delfosse 2005; Taylor et al. 2007). So why are these agents approved for release? As Willis et al. (2003) found, in every instance the benefits (i.e. control of the target alien plant) were deemed to be greater than the perceived risks of releasing the agent (i.e. damage to non-target species). Such decisions were not quantified in any standardised manner despite their obvious importance in the decision making process to determine the greater of two potential risks (i.e. from the agent and the target).

Target risk

Despite wide acknowledgement of the threat posed by alien plants to native species and the role of biological control in reducing such threats (Loope et al. 2004), assessments of the potential damage caused by target alien plants are rarely incorporated into benefit-risk analyses. Information on the native species threatened by alien plants is also depauperate, despite wide acknowledgement of the threat posed (e.g. Adair and Groves 1998; Richardson and van Wilgen 2004; Downey et al. 2010b). Thus for alien plants like *L. camara* that threaten large numbers of native species (Turner and Downey 2010), the benefits of biological control are likely to be significantly underestimated. Some evidence of benefits from biological control have recently been documented, for example the recovery of native species five years after the release of a biological control agent to control *Miconia calvescens* in Tahiti (Meyer et al. 2011) and the successful biological control of *Ageratina riparia* in New Zealand which is likely to have saved several endangered plant species (Barton et al. 2007). The lack of data on the (i) number of native species that are threatened by alien invasive plants, and (ii) benefit to native plants provided by biological control has contributed to the absence of any kind of formal evaluation of the 'target risk' in biological control release assessments. As Willis et al. (2003) review highlighted, incorporation of an unquantified qualitative description of the 'target risk' can have important implications for deciding whether to release an agent with predicted low levels of non-target damage.

Whilst it is not always possible for biological control programs to collect data on non-target impacts from specific target alien plant species, the discipline, decision and policy makers, as well as regulatory authorities should continue to work with other disciplines to ensure that such data is collected and made available. For example, Coutts-Smith and Downey (2006) outlined how decisions about managing the threat from alien plants could substantially be improved (i.e. for almost half of the 419 threatened species examined) if researchers working on threatened species had documented the actual alien plant threat rather than describing threat generically as being caused by weeds. It is however possible for biological control researchers to collate available information on species threatened by target alien plants from the literature and databases like those complied by Coutts-Smith and Downey (2006) in Australia, Wilcove et al. (1998) in the US and the IUCN Red list (IUCN 2015) globally.

Considering multiple risks: the value of like-for-like risks

Multi-criteria analysis approaches are increasingly being used to assist decisions between alternatives in environmental management (see Mendoza and

Martins 2006; Linkov et al. 2006), although their application to alien plant management is rare (Cook and Proctor 2007; Benke et al. 2011; Sinden et al. 2013). Such multi-criteria analysis methods incorporate criteria on a range of environmental, economic, social, and organisational performance, thereby assisting choices with multiple objectives and alternatives. Despite this approach having merit for assessing and managing the complete risk of releasing a biological control agent, no such assessment has been done.

Consideration of the relative risk of non-target damage to native species from the combination of an agent and its target alien plant into the assessment process of releasing agents does not involve assessing alternative choices, but rather the inclusion of a like-for-like comparison. We are therefore advocating for the inclusion of both risks (i.e. agent and target risk as a collective) in the decision making process, not a choice of two alternative risks.

A proposed framework for considering like-for-like risks

Here we outline an assessment framework that can be used to evaluate the non-target agent risk against that of the target (i.e. to native species). The proposed framework uses matrices to assess the same (or like-for-like) risk, being non-target damage, from two perspectives (agent and target) (Tables 1, 2). Incorporation of other risks would require a multi-criteria comparative risk approach (e.g. Benke et al. 2011) and decisions about alternatives (see above). These risk matrices encompass an assessment of the consequence of the non-target damage from an agent (Table 1) and the target (Table 2), being benign through to catastrophic, and the likelihood of non-target damage, being very unlikely through to very likely, along with an indicative description of what each category encompasses and the criteria for selecting each (Supplementary tables S1 and S2). Each of the 16 cells in the risk matrices is given a risk rating (high, medium, low or minuscule) and a description of an indicative outcome.

When determining the criteria for assessing the likelihood and consequence for the agent risk, we used the ‘worst’ case example of non-target damage from the literature of a deliberate introduction of a biocontrol agent being *R. conicus* to establish the very likely and catastrophic criteria (Supplementary table S1). Whilst *C. cactorum* in the USA provides another ‘worst’ case example, it was not used due to its atypical introduction history (see discussion above) and because the proposed framework is designed for regulated releases. Also we could not use *C. cactorum* in the framework as there is no target in the USA and to evaluate the risk, an assessment of the potential for the agent to disperse from the Caribbean to the USA would also be needed. These worst case criteria were then used as a benchmark when establishing the remaining criteria. A similar process was used for determining the likelihood and consequence criteria for targets, in which the ‘worst’ case example from the literature was *Lantana camara* (Supplementary table S2).

In the third step of the framework, a matrix was used to assess the combination of the agent and target risk (Table 3). The combination of risk ratings from each assessment provides an overall risk rating for the non-target damage (Table 3). In addition, we provide a description of the nature of the risk with respect to making decisions around the level of risk which might be deemed acceptable. Our rating B “further testing is required” is not designed to pick up problems with host-specificity test lists (as is the case with *Aconophora compressa*) as there is already a process for this available (see Wapshere 1974; Briese 2003). Instead our rating B is designed to ensure that decision makers have sufficient information in order to accept or reject an agent based on the level of risk predicted. The outcome of rating B is that in order to make such a decision more information is needed. Similar approaches have been proposed in the context of biological invasions (e.g. Simberloff and Alexander 1998) but not in the context of biological control to the best of our knowledge.

Account for uncertainty

The use of host-specificity testing of biological control agents prior to release significantly reduces the level of uncertainty associated with the decision supported by reviews of non-target damage from released agents which shows the level of unpredicted non-target damage to be extremely low, especially since the adoption of stringent host-specificity testing (Fowler et al. 2000; Suckling and Sforza 2014). Additionally,

Table 1 Agent risk matrix—the risk event is non-target damage following the release of a biological control agent, which is a combination of the consequence and likelihood of the risk occurring

Likelihood (of non-target damage from the agent)	Consequence (of non-target damage from the agent): Catastrophic	Pervasive	Negligible	Benign
Very likely	**High** non-target effects are certain and will be very destructive	**Medium** non-target effects are certain and will be damaging	**Medium** non-target effects are certain and will result in minor, or sporadic damage	**Low** non-target effects are certain, however such effects will not result in measurable damage
Likely	**High** non-target effects are likely and will be very destructive	**Medium** non-target effects are likely and will be damaging	**Low** non-target effects are likely and will result in minor damage	**Minuscule** non-target effects are likely, however such effects will not result in measurable damage
		A. nigriscutis	*N. gunniella*	
Unlikely	**Medium** non-target effects are unlikely despite being very destructive	**Medium** non-target effects are unlikely despite being potentially damaging	**Low** non-target effects are unlikely and any damage will be minor	**Minuscule** non-target effects are unlikely with no measurable damage
		G. calmariensis	*A. compressa*	
			D. elongata	
		G. pusilla	*P. vitalbae*	
Very unlikely	**Low** non-target effects are extremely unlikely despite being potentially very destructive	**Low** non-target effects are extremely unlikely despite being potentially damaging	**Minuscule** non-target effects are extremely unlikely and any damage will be minor	**Minuscule** non-target effects are extremely unlikely with no measurable damage

A risk rating and a description of the likely outcome of the assessment is presented for each of the 16 cells of the matrix. The six examples of agents posing non-target damage outlined in Table 4 have been assessed using the criteria in Supplementary table S1 to determine their risk rating for consequence and likelihood. Shading in the cells represent the level of agent risk with white being high, pale-grey being medium, intermediate-grey being low, and dark-grey being minuscule

we used the terms threat and impact (as defined by Downey et al. 2010b) to account for some of the uncertainty associated with the non-target damage from target alien plants in the assessment criteria, in that impacts are measurable/quantifiable, and threats are assumed but uncertain (see Supplementary table S2).

Using the framework

We identified six examples from the literature for which there was sufficient information on the non-target effects from both agents and their target alien plants (i.e. a like-for-like assessment) to populate the matrices (Tables 4, 5). We included three examples from the USA, two from Australia and one from New Zealand, which span a range of agents and targets (including life forms). For many of the agents with non-target damage to native species, information on the non-target damage from their target alien plants to native species was lacking or not quantified in a way that could be used here, despite extensive searches of the literature. For example, the collective risk from the combination of *Carduus nutans* and *R. conicus* could not be assessed, because despite sufficient information on the agent, very little information on the impact of the target alien plant to native species could be found.

Table 2 Target risk matrix—the risk event is impacts to native species from alien plant biological control targets, which is a combination of the consequence and likelihood of the risk occurring

Likelihood (of impact to native species from the target alien plant)	Consequence (of impact to native species from the target alien plant): Catastrophic	Pervasive	Negligible	Benign
Very likely	**High** impacts to native species are certain and will be very destructive	**Medium** impacts to native species are certain and will be damaging	**Medium** impacts to native species are certain and will result in minor damage	**Low** impacts to native species are certain but will not result in measurable damage
	L. camara	*L. salicaria* *M. pigra* *Tamarix* spp.		
Likely	**High** impacts to native species are likely and will be very destructive	**Medium** impacts to native species are likely and will be damaging	**Low** impacts to native species are likely and will result in minor damage	**Minuscule** impacts to native species are likely but will not result in measurable damage
	C. vitalba *E. esula*			
Unlikely	**Medium** impacts to native species are unlikely despite being very destructive	**Medium** impacts to native species are unlikely despite being potentially damaging	**Low** impacts to native species are unlikely and any damage will be minor	**Minuscule** impacts to native species are unlikely with no measurable damage
Very unlikely	**Low** impacts to native species are extremely unlikely despite being potentially very destructive	**Low** impacts to native species are extremely unlikely despite being potentially damaging	**Minuscule** impacts to native species are extremely unlikely and any damage will be minor	**Minuscule** impacts to native species are extremely unlikely with no measurable damage

A risk rating and a description of the likely outcome of the assessment is presented for each of the 16 cells of the matrix. The six examples of target alien plants posing non-target damage outlined in Table 5 have been assessed using the criteria in Supplementary table S2 to determine their risk rating for consequence and likelihood. Shading in the cells represent the level of target risk with white being high, pale-grey being medium, intermediate-grey being low, and dark-grey being minuscule

In each of these six examples, the non-target damage [consequence] from the alien plant was either catastrophic or pervasive, which is partly an artefact, in that most biological control is focused on controlling the 'worst' alien plant species. The target risk to non-target species, in all six examples, is higher than the agent risk, despite the criteria for agents being lower in terms of the number of species affected (Supplementary tables S1 and S2). Agents that have a high non-target risk for which their target alien plant poses a low impact should be avoided, whilst agents that pose a low or minuscule non-target risk for which their targets pose a very high impact should be sought. Whilst these examples reflect actual releases, the proposed framework is designed to assess new agents for release, or alternatively to make decisions about starting a new program. In such instances the proposed tool may help decision makers to decide if focusing on a target with low impacts is warranted or not.

Our assessment shows that for four of the examples the risk could be deemed to be low given the low level of non-target damage observed by the agent and the high level of non-target damage posed by the target alien plant. Two of the examples illustrate that, despite high level of non-target damage from the target alien plant, the level of non-target damage from the agent is such that the overall level of risk could be deemed unacceptable. For the first example, despite the non-target damage from *Aphthona nigriscutis* being density-dependent (Baker and Webber 2008), its

Table 3 Combined matrix of the agent and their respective target risks, from Tables 1 and 2 respectively

Target risk assessment outcome (from Table 2)	Agent risk assessment outcome (from Table 1): High	Medium	Low	Minuscule
High	C	B	A	A
		A. nigriscutis on E. esula	*A. compressa* on *L. camara*; *P. vitalbae* on *C. vitalba*	
Medium	C	B	A	A
		G. calmariensis & G. pusilla on L. salicaria	*D. elongata* on *Tamarix* spp.; *N. gunniella* on *M. pigra*	
Low	C	C	B	A
Minuscule	C	C	B	A

Risk rating	Description
A	The level of non-target damage is considered to be low and an appropriate level of risk has been demonstrated for a release.
B	The level of non-target damage is such that further testing is required to ensure that an appropriate level of risk is achieved before a release is made.
C	The level of non-target damage is deemed unacceptable and thus agents with this rating should not be released.

A description of the combined risk rating (A, B or C) is presented in the table below. The six examples are presented along with their respective combined risk rating. Shading in the cells represents the three different combined risk ratings A, B and C

release on *Euphorbia esula* should have warranted more stringent assessments (as opposed to reject) based on our framework. For the second example, the potential of *Galerucella calmaiensis* and *G. pusilla* to feed on non-target native plants also may have warranted further assessment. In this case, the damage to native plants from the agent has no lasting negative consequences as predicted from host specificity testing (Blossey et al. 2001a, b).

Despite not having data on the non-target effects to native species for many of the target alien plants, inferences or assumptions could be made as to the likely risk level (i.e. in Table 2). For example, if we assumed that many of the native thistles threatened by *R. conicus* were also likely to be threatened by *C. nutans* in the USA (i.e. through competition), we might assign *C. nutans* [target] a likely and catastrophic non-target impact to native species (see Supplementary table S2). *Rhinocyllus conicus* [agent] in this case would be assigned very likely and catastrophic (see Supplementary table S1), which collectively would result in an unacceptable level of risk (i.e. from the combined agent-target matrix (Table 5)). Even if there was a major positive net benefit from the introduction of *R. conicus,* due to very high negative impacts of *C. nutans* to native species before control, our framework would not support its release, in line with other conclusions that *R. conicus* would not be released today (Delfosse 2005; Suckling and Sforza 2014). We have reduced subjectivity by outlining a range of criteria for each risk category for both the agent and target, based on information in the literature and the use of 'worst case' examples as benchmarks (see Supplementary tables S1 and S2). As new information becomes available the criteria in Supplementary tables S1 and S2 can be refined.

It is important to note that the outcome of the framework is not a reflection of the degree to which an agent should be released. We have just discussed this here in the context of actual examples. Instead our

Table 4 Examples of non-target damage from biological control agents released to control alien plant targets

No.	Target	Agent	Country	Non-target damage			Justification for release	Outcome of release #	References
				Species	Native/ Alien	Predicted			
1.	*Euphorbia esula* (leafy spurge)	*Aphthona nigriscutis*	USA	*Euphorbia robusta*	Native	Identified as a potential host species, but not tested	Not applicable	(i) Non-target damage, which declined with declining populations of the target, which subsequently recovered, and (ii) significant control	Pemberton (1985); Baker and Webber (2008)
2.	*Lythrum salicaria* (Purple loosestrife)	*Galerucella calmariensis* *Galerucella pusilla*	USA	*Lythrum alatum* *Decodon verticillatus*	Native Native	Yes – potential from host-specificity testing (specifically *L. alatum*)	Survival unlikely	(i) Non-target damage is minimal, confined and temporal, and (ii) high, but variable, depending on flooding regime	Blossey et al. (2001b); Kok et al. (1992); Dávalos and Blossey (2010)
3.	*Tamarix* spp. (salt cedar)	*Diorhabda elongata*	USA	*Frankenia salina*	Native	Yes – potential from host-specificity testing	Poor survival and low levels of damage	(i) Non-target damage is minimal under worst case scenario, and (ii) substantial damage	Dudley and Kazmer (2005)
4.	*Lantana camara* (lantana)	*Aconophora compressa*	Australia	Ornamental fiddlewood tree (*Citharexylum spinosum*), and a 'spillover' effect on other ornamental plants	Alien	No – *C. spinosum* not tested	Not applicable	(i) High but isolated – all damaged confined to alien plants, and (ii) some damage observed	Palmer et al. (2010)
5.	*Mimosa pigra* (mimosa)	*Neurostrota gunniella*	Australia	*Neptunia* species	Native	Yes – predicted from host-specificity testing.	Agent would not persist or have substantial effects in the field	(i) Low level of non-target damage observed, and (ii) severe damage to target	Palmer et al. (2010); Davis et al. (1991); Taylor et al. (2007)
6.	*Clematis vitalba* (Old man's beard)	*Phytomyza vitalbae*	New Zealand	*Clematis foetida* *Clematis forsteri*	Native	Yes – predicted from host-specificity testing (*C. foetida*)	Risk of significant damage to non-target plants is negligible to low	(i) Minimal level of non-target damage observed, and (ii) minor, but significant level of damage	Hill et al. (2001); Paynter et al. (2004); Paynter et al. (2008); Paynter et al. (2006)

Outcome of release (i) is the outcome with respect to non-target damage, and (ii) is the outcome in terms of control of the target alien plant species

Table 5 Examples of non-target damage from target alien plant species

No.	Target	Country	Non-target damage	References
1	*Euphorbia esula* (leafy spurge)	USA	32 common native plant species More than two species of native herbivores Two native bird species	Belcher and Wilson (1989); Butler and Cogon (2004); Trammell and Butler (1995); Scheiman et al. (2003)
2	*Lythrum salicaria* (Purple loosestrife)	USA	Reduction in native plant species (at least two species) Six bird species	Blossey et al. (2001a)
3	*Tamarix* spp. (salt cedar)	USA	12 native bird species Arthropods and insect pollinators One native fish	Brand et al. (2010); Pendleton et al. (2011); Kennedy et al. (2005)
4	*Lantana camara* (lantana)	Australia	1,321 native plant and 158 native animal species (275 native plant and 24 native animal species require immediate protection)	Turner and Downey (2010)
5	*Mimosa pigra* (giant sensitive plant)	Australia	Decrease in native species (flora e.g. more than 5 tree species + others, and fauna two birds and two reptiles)	Braithwaite et al. (1989)
6	*Clematis vitalba* (Old man's beard)	New Zealand	35 native plant species	Ogle et al. (2000)

The targets are the same as those in Table 1 with the same number

framework provides a way of holistically balancing risks to help managers, decision makers and regulatory authorities responsible for granting permission to release agents an extra tool to determine the level of risk they are prepared to accept when assessing agents for release or targets to work on.

Discussion

To improve biological control outcomes, processes are needed to better understand the impacts of both the agent and target alien plant (Thomas and Reid 2007). In one such attempt, Moran and Zimmermann (1984) used a matrix-based approach to evaluate the success of individual biological control agents. Whilst this approach provided a framework to consider both the target and agent, it was not adopted or used for assessing the risks or non-target impacts. Additionally, whilst Hirose (1999) proposed the concept of categorising non-target effects/impacts, this approach does not seem to have been adopted, for either the agent or the target.

The lack of a framework or process that accounts for the effects of the target alien plant as well as the agent has led to many inconsistencies in the level of risk that is deemed to be acceptable and approval of agents. For example, agents are released despite predictions of non-target damage to native species (e.g. Paynter et al. 2004).

Whilst consideration of the target risk has been made when releasing some agents, there is no standardised framework for comparing such risks. In virtually all instances the justification provided for the target risk is qualitative, with no guidance provided on how such assessments were undertaken. Thus the target risk is not given the same level of precision or assessment as that given to assessing the risk from the agent. Given that the regulatory authorities responsible for granting permission to release biological control agents in some countries have adopted a risk-averse position by focusing on only a subset of the risks, it is imperative that a more robust process is adopted which accounts for the target risks. When such assessments have been given a more equal emphasis the focus of the risk changes. For example, whilst Pearson and Callaway (2008) outlined major indirect non-target effects associated with the release of a biological control agent to control spotted knapweed (*Centaurea stoebe*), the authors also acknowledged that these effects dwarfed the direct negative effect of controlling spotted knapweed with herbicides. Also Blossey et al. (2001a) concluded that the negative impacts justified the need for biological control of purple loosestrife (*Lythrum salicaria*), as the potential benefits outweighed any potential risks.

Because there is no standardised approach or mechanism for inclusion of the target risk in the assessment system for biological control releases, decisions can become constrained due to misplaced emphasis on the potentially lesser of the two risks. For example, Dudley and Deloach (2004) highlighted how non-target effects on a single native species from a biological control program managed to override evidence of the multiple native species affected by the alien target. This situation would have been prevented if a system that compares the relative risks was available.

Risk-averse or risky?

The major drawback of adopting a risk-averse position is that decisions tend to be made based around outcomes with a higher chance of success, even if the potential benefits are lower. As illustrated by Hinz et al. (2014), the current risk-averse position is not necessarily resulting in optimal outcomes. Not releasing some agents that attack native plants may endanger other native species through the effects of the target alien plant (Harris 1988). Moreover, excessive caution associated with a risk-averse position can be counter-productive (and costly) when it inhibits beneficial biological control programs (Dudley and Kazmer 2005).

Despite the regulatory authorities adopting a risk-averse position, numerous agents have been released for which adverse risks were known through host-specificity testing. In addition, the level of risk deemed acceptable in these instances varies considerably, often being offset by the perceived benefit, which is not always assessed adequately. Moreover, such decisions are not made using a consistent framework and levels of risk that are deemed acceptable differ between countries (see Hinz et al. 2014). Thus a framework is needed to ensure that such decisions and the level of risk deemed acceptable is comparable across releases. Whilst the inclusion of increased risk assessment procedures has resulted in increased costs of biological control (Fowler et al. 2010), the resultant increase in transparency and lack of overt political involvement has significant benefits (Barratt and Moeed 2005; Shaw et al. 2011).

Determining the value of including the target risk

Ferraro and Pattanayak (2006) outline the importance of including an evaluation framework in conservation practices, not just in terms of determining the outcome of management, but also in terms of evaluating and improving decision making processes and frameworks [adaptive management], and Bull et al. (2014) highlight the importance of having baseline data for making and evaluating conservation decisions. Whilst host-specificity tests can be used to evaluate the agent risk and post-release evaluations of non-target effects can be used to assess the effectiveness of such tests, no such system exists for the target risk. A similar situation exists with respect to baseline data on establishing non-target damage.

Given the low level of post-release evaluations of non-target effects undertaken (see Paynter et al. 2004) and the paucity of data on the actual impacts from alien plants on specific native species (see Blossey 1999), it is critical that appropriate data be collected to adequately evaluate the target and agent risks in the future, which can also be used to assess the framework proposed. We provided specific criteria for determining the level of non-target damage (both likelihood and consequence) for both agents and targets (Supplementary tables S1 and S2), for which evaluations of the proposed framework can be undertaken in the future. Approaches to collect such data currently exist (e.g. Paynter et al. 2004; Turner and Downey 2010).

Other risks

The framework presented here enables the comparison of like-for-like risks associated with non-target damage to native species from both the agent and its target alien plant to be incorporated into a decision making process. Accounting for the full gamut of risks, however, would require a multi-criteria analysis (e.g. Mendoza and Martins 2006) and a thorough examination of all the possible risks, alternatives and benefits. Examples of other risks include the risk of agents failing to establish or impact upon the target plant (McClay and Balciunas 2005) or the risk of broader non-target effects [i.e. multi-trophic effects

(Carvalheiro et al. 2008)]. Our ability to evaluate such risks can be problematic, for example, the risk of an agent failing to establish in the field or impact upon the target species. The desired management outcome will determine the type of risk that should be included as well as the specific criteria needed to evaluate such risks (Downey et al. 2010a). Here we focused on the non-target effects to native species.

In conclusion, whilst we have outlined how the inclusion of assessments of both the agent and target risks can result in a more holistic understanding of the risk of releasing a biological control agent, this work has illustrated that the science of biological control needs to determine the level of risk that is deemed acceptable, once the target risk is incorporated. We argue that a slightly less risk-averse position could be adopted if a framework for making decisions was available, because without a framework, risky decisions could be made despite the risk-averse position adopted by the authorities responsible for decisions on releases.

We have highlighted here how already existing risk assessment approaches can be used in biological control assessments without major modification, and that these approaches are grounded in legislation and polices globally and thus increasing the likelihood of their adoption for biological control more broadly. We have used the literature and actual examples to construct our framework, which should also help with its adoption. Moreover, there is a need to include the target risk into the decision making processes for releasing biological control agents, in a formalised manner. Whilst we have proposed a framework, post-release monitoring and evaluation of both the agent and target, including non-target effects, must underpin and be formally incorporated into any risk assessment approach that is developed and should also be used to assess its effectiveness.

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