Review

Assessing safety of biological control introductions

Barbara I.P. Barratt*

Address: AgResearch Invermay, PB 50034, Mosgiel, New Zealand.

*Correspondence: Email: barbara.barratt@agresearch.co.nz

Received: 4 September 2011
Accepted: 4 October 2011
doi: 10.1079/PAVSNNR20116042

Abstract

Biological control is an important component of pest management systems. It was generally considered safe and sustainable until the validity of this consensus was challenged by researchers who pointed out that there was a lack of study, and hence evidence, to support it and provided examples of non-target impacts. Biosafety of biological control subsequently received considerable attention from both biocontrol practitioners and regulators. Many countries now have legislation in place, which is focused on risk assessment for biological control and protecting native and valued biota and the environment from potential adverse impacts. This review summarizes the biosafety debate and characterizes the direct and indirect risks of biological control mainly for weeds and insect pests. During a biological control programme, there are several ways in which aspects of biosafety can be considered and addressed: exploration in the native range of the target species; from literature and knowledge of the biological control agent and host; experience from use of the biological control agent elsewhere; and host-range tests. The value of post-release monitoring and retrospective studies for validation of pre-release predictions is discussed. A poorly studied aspect is analysis of the population impacts of non-target attack by biological control agents. The literature from the last 20–30 years can help define some useful principles by which a risk assessment can be conducted to minimize adverse environmental effects. It has become clear over this period that comprehensive assembly of information and robust quarantine testing to provide a well-structured risk assessment can reduce uncertainty in decision-making in this area.

Keywords: Biological control, Biosafety, Risk assessment, Non-target effects, Regulation

Review Methodology: Literature was accessed on a regular basis using alerts generated by OvidSP in order to update the bibliography of the BIREA database [1]. The searches include CAB Abstracts and BIOSIS databases and the search terms used were safety, biosafety, non target, nontarget, host-range testing, host specificity, risk assessment, post release, host range, biological control, biocontrol. Journals also scanned on a regular basis include Biological Control, BioControl, Biocontrol News and Information, Environmental Entomology and Entomologia Experimentalis et Applicata. A number of books published on the subject of risks of biological control were consulted [2–6].

The scope of this review is mainly classical biological control. A recent review of inundative biocontrol reports on the trend away from the use of exotic organisms by commercial producers, partly because of the increase in regulatory demands [7], and the ERBIC programme (see below) reported results on biosafety research for inundative biological control [8]. In addition, the emphasis of this contribution is on insects used for biological control of weeds and insect pests, with some reference to predators and pathogens as biological control agents. The literature on biosafety of predator introductions includes many examples of research on ladybirds (Coleoptera: Coccinellidae) [9–13] and tachinids (Diptera: Tachinidae) [14, 15], and prediction and assessment of non-target impacts of pathogens used for biological control has been well reviewed [16–19].
Biological Control Safety: The Debate

Biological control was heralded as one of the safe alternatives to pesticides when public demands to reduce pesticide use were made in the 1960s and 1970s. This pressure arose partly as a result of concerns about environmental risk, prompted not only by Rachel Carson in her landmark publication 'Silent Spring' [20] but also by the increasing incidence of pesticide resistance, and the promotion of the philosophy of sustainable agricultural practices. Several prominent biological control researchers provided assurances that biological control was environmentally safe and risk-free [21]. This view was not shared universally by scientists, but, in particular, the environmental safety of biological control was questioned [22–26]. It was pointed out that in comparison with the application of pesticides, biological control is irreversible, self-perpetuating and self-dispersing, attributes clearly considered among the benefits of biological control by some, but factors alerting others to the potential environmental implications of such introductions. Views remained highly polarized for several years, especially in Hawaii where biological control has been particularly intensively practised [27]. Proponents of biological control claimed that the 'conservationists' had no evidence for negative impacts of biological control and that claims of adverse impacts were overstated, often using examples either from the past before consideration was given to risk, or the more visible consequences of vertebrates used for biological control [27–30]. In recent years, however, funding has become available for research in this area and it has presented an opportunity to conduct challenging ecological research [31, 32]. In response, a number of meetings and workshops were held to present research and establish research priorities in risk assessment for biological control [2, 5, 33, 34].

The European Union funded a 4-year programme involving five partner countries, titled 'Evaluating environmental risks of biological control' or ERBIC. One of the main objectives of this programme was to ensure that the introduction of biological control agents does not put non-target organisms at risk. With the emphasis mainly on either seasonal inulative or inudative releases rather than classical biological control, the ERBIC study set out to determine the negative and positive impacts of biological pest control, to develop methods to assess risk, and to design specific European guidelines to ensure environment safety. The final report [8] stated that the research had shown that 'biological control overall has been extraordinarily safe', but that this can still be improved using risk assessment methods developed during the project. Furthermore, the authors concluded that decision tools to choose the safest from a number of candidate biocontrol agents were now available, to decide what information is needed for a full risk assessment, and to determine whether particular natural enemies were not suitable for release.

Regulations and Guidelines

While biological control biosafety was still being debated, regulators in some countries began to review their legislation. Australia and New Zealand were allegedly the front-runners with their Biological Control Act (1984) (Australia is the only country with specific legislation) and the Hazardous Substances and New Organisms Act (1996) (HSNO), respectively. A global review of risk-cost–benefit analyses for weed biological control agents introductions globally concluded that only New Zealand came near to a complete and transparent process [35]. However, it was pointed out that Australia, unlike New Zealand, requires the submission of a test plant list for approval (by agricultural and conservation agencies) for host specificity testing of weed biological control agents, before an application to release is accepted. This 'Nomination of Target Weeds for Biological Control' to the Australian Weeds Committee can result in a requirement for more test species to be added to the list.

It was later suggested that Europe lagged behind Australasia and North America in implementing legislation for biological control, partly because Europe has more often been the exporter of biological control agents, rather than the recipient [36]. An agreed approach to regulation of biological control introductions between countries in Europe appeared to be an obvious requirement since biological control agents are highly likely to spread across borders [37] and it was clearly argued that for risk assessment, ecosystems would be more relevant than national boundaries [38]. The need for consistent standards in regulation of biological control was recognized [39], and a detailed history of efforts in Europe to achieve adoption of 'harmonized' regulation for biological control was compiled [36, see Table 1].

Biological control practitioners have generally accepted that regulation of biological control agent introduction is required in the public interest because of its irreversibility and the potential for biological control agents to disperse to habitats other than those where they were released [40]. In New Zealand, for example, the Hazardous Substances and New Organisms (HSNO) Act 1996 [41] requires that new organism introductions, including biological control agents, must be compatible with safeguarding the life-supporting capacity of air, water and ecosystems, the sustainability of flora and fauna, and the intrinsic value of ecosystems (Section 36 of the HSNO Act, 1996). The Environmental Protection Authority, formerly the Environmental Risk Management Authority New Zealand, has responsibility for implementation of the HSNO Act [42].

In 1995, the Food and Agriculture Organization (FAO) Council ratified an international 'Code of Conduct for the Import and Release of Biological Control Agents', with the intention of providing a set of standards and guidelines for 'best practice' biological control agent introduction [43], and this has recently been updated [44]. It is
recommended in the Code that proposed importers of biological control agents should provide information on agricultural and environmental non-target effects. A number of other international agencies have developed similar guidelines and recommendations, and with the intent of harmonizing biological control regulations in Europe, a commission of the International Organisation for Biological Control, Western Palearctic Regional Section (IOBC-WPRS) was established and a document merging these guidelines was produced [45]. A review of more recent developments in Europe in the regulation and environmental risk assessment of invertebrate biological control agents remarked again upon the variable and fragmented adoption and implementation of guidelines [46]. It has been further recommended that risk assessment for biological control agents should be globally harmonized [13].

What are the Risks?

The risks that have been identified for biological control introductions can be categorized as direct and indirect effects [47, 48]. Direct effects are usually recognized as impacts that a biological control agent might have on organisms other than the target in the new environment into which it has been released [22, 49-51]. Hence, attack on non-target species in the same trophic level as the target is clearly the most obvious direct effect, and can include effects on native non-target species, beneficial or valued exotic species [52, 53], or effects on other pests [47], sometimes termed as ‘fortuitous biological control’ [54, 55]. An example of the latter occurred when Microctonus aethiopoides Loan was introduced into New Zealand to control Sitona discoideus Gyllenhal, a pest of lucerne, and it was discovered that the parasitoid also attacked Listronotus bonariensis (Kuschel), an introduced pest of ryegrass [56].

Indirect effects can include impacts on species in the same trophic level as the biological control agent, such as other parasitoids, e.g. hybridization [57, 58], competition or displacement [59-62], or impacts on other organisms in other trophic levels and ultimately on food webs [34, 63-65].

It is generally acknowledged that generalist predators are less likely to meet biosafety standards required by regulators because of the potential for non-target impacts [14, 15, 66], and it has been recommended repeatedly that generalist natural enemies should not be considered for biological control [25, 67-69].

It has been predicted that in the future climate change might introduce a new element of risk as a result of ‘uncoupling’ of biological control, as a result of a change in the fitness of biological control agents and their hosts; differential phenological changes between host and natural enemy [70]; changes in distribution of hosts and range expansion of natural enemies [71]; and other impacts that will be difficult to predict. These impacts also have the potential to create risk for non-target species, resulting from the same drivers.

Assessment of Biological Control Safety

During a biological control programme, there are several ways in which aspects of biosafety can be considered and addressed: during exploration in the native range of the target species to identify natural enemies; from literature and knowledge of the characteristics of the biological control agent and host; experience of biosafety where the biological control agent has been used elsewhere; host-range tests that can be carried out in the native range, or in quarantine in the proposed country of introduction, and from post-release monitoring of realized host range. The latter is clearly ‘after the fact’; however, such studies aimed at validating predictions add considerable value to the information resource available for future decision support [68, 72]. These aspects of risk assessment will be reviewed below.

Once a target pest has been identified as the subject of a biological control programme, exploration in the native range of the host is usually the first step in determining the suite of natural enemies from which potential biological control agents could be selected. As the exploratory work in the native range begins to focus on potential effective candidate biological control agents, the opportunity is increasingly being taken by researchers to determine the natural host range of these agents as part of these investigations [73-80]. This information can assist predictions to be made regarding the potential risk of the biocontrol agent in the receiving environment. For example, research carried out in Europe on host range of parasitoids of the polyphagous plant bugs Lygus spp. (Hemiptera: Miridae) showed in the laboratory that Peristenus digonatus Loan (Hymenoptera: Braconidae) attacked all non-target mirid species to which it was exposed, at quite high levels of parasitism, but that in the native range in the field, parasitism levels in mirid species were below 1% [75]. Post-release surveys in eastern North America confirmed that some non-target parasitism has occurred but at negligible levels [81].

An example from weed biological control is provided by the well-documented case of Rhinocyllus conicus Froelich, introduced from Europe to North America for biocontrol of thistles in the genus Carduus [82]. Studies in Europe in the native range of R. conicus showed that this insect attacked thistles in genera other than Carduus [83]. However, releases went ahead on the rationale that Carduus was clearly a preferred host and that there were host-specific biotypes of R. conicus in Europe, which accounted for the apparently wide host range. Furthermore, little host-range testing was carried out in North America, and what was done focused mainly on economically important crops [83]. It is now well documented that
R. conicus attacks native North American Cirsium species to the extent that it is having a population impact on species such as the prairie grassland Platte thistle, Cirsium canescens Nutt, substantially reducing viable seed production by the plant [84].

Simulation modelling using data from the natural range in addition to quarantine studies can assist in predicting non-target impacts [85]. The cost-effectiveness of native range research for CSIRO has been clearly demonstrated [86].

The importance of accurate taxonomic identification of the proposed biological control agent (and host) is clearly of paramount importance to assessing risk [87]. Definitive identification of the organism is usually required by regulators as part of the dossier supporting the application to introduce a new biological control agent. The current taxonomic status of the organisms and past synonymy [88] is essential both to search and compile literature on the organism, and to help determine potential non-target hosts for biosafety testing [87]. Similarly, the correct taxonomic identity of the target species in both the natural range and in the area where it is being targeted as a pest is required to support prediction of potential non-target hosts. Such work is becoming increasingly dependent on molecular methods of organism characterization [35, 89].

Recent research has shown several instances where different 'biotypes' of biological control agent species have different host ranges, which has become a further consideration for risk assessment [90–92]. In New Zealand, biological control agent biotype has been a condition of a release for some introductions, such as M. aethiopoides for biological control of Sitona lepidus (Gyllenhal) to ensure that once permission to import an organism has been given, that future importations are permitted only for the same biotype, with the same host-range characteristics [93]. The wisdom of this decision was exemplified when, in quarantine testing, it was shown that hybridization between the existing Moroccan and European biotypes of M. aethiopoides could potentially compromise the biocontrol programmes for the two species of Sitona that they were intended to control [94]. A solution was found when a parthenogenetic biotype of M. aethiopoides was discovered in Ireland, which was both effective against S. lepidus and with a narrower host range than the Moroccan biotype [93].

Available literature can be a valuable resource for initial assembly of information to support risk assessments for biological control agents, especially to collect negative evidence of attack, since there are more published data on the natural enemies of a particular host, than hosts used by a particular natural enemy species [87, 95]. Online information resources and databases are also available [1, 96, 97] to assist biocontrol practitioners to carry out risk assessments. Detailed knowledge of the biology and ecology of the target species [99] can assist with the prediction of likely success of a biological control programme, and also to balance this with potential risks, both directly to non-target species and indirectly in food web effects. However, it has been suggested that the best way of avoiding indirect impacts is to select highly specific biological control agents [99].

The prediction of potential non-target hosts of a proposed biological control agent in a new area of introduction requires good information on the flora/fauna of the receiving environment and their taxonomic affiliations with the target, so that a list of species potentially at risk can be developed [100, 101]. Some geographical regions are in a better position than others for this to be achieved, and clearly, some taxa will be better known than others. Robust data on the biosafety record of a candidate biological control agent in areas where it has been introduced previously should provide a valuable indication of likely non-target impacts [87, 102]. However, while there are many examples of biological control agents being transferred between countries [103], biosafety data are not often available mainly because of the lack of resources to carry out post-release impact assessment following a biological control release [29, 104].

**Host Specificity Testing**

The question of host specificity in biological control agents has been a topic of intense debate ranging from the view that the presence of alternative hosts can assist during periods of absence of the target [67, 105], to insistence that introduced biological control agents should be demonstrated to be highly host-specific. Most guidelines and regulations now require that host specificity testing, normally undertaken in quarantine, is an important component of an environmental risk assessment for biological control agents. In addition, quarantine containment is required to ascertain that the consignment of proposed biological control agents is free from associated organisms such as hyperparasites, pathogens or other contaminating organisms. Clearly, these could pose a risk to the biological control programme itself, or present a biosecurity risk [106].

Results from laboratory host-range tests are often the data resource on which risk assessments depend most heavily, despite evidence that laboratory testing in artificial conditions can provide misleading results such as overestimation of host range [39, 107–110]. Given this well-acknowledged constraint, laboratory host-range testing requires a number of questions to be addressed. What should be included in the test species list, what sort of tests should be carried out, what other considerations are important for meaningful tests and how do we interpret the data [108]?

In the case of weed biological control agents, test species selection has heavily relied upon the 'centrifugal phylogenetic testing' regime, in which plant species are tested in a sequence from those most closely related to
the target weed, to those more distantly related [111]. This testing sequence was later modified to avoid rejection of biological control agents after cage testing that predicted a wider host range than observed in the field [112]. It was argued that cage conditions were removing the natural behavioural 'filters' and environmental cues used by insects in the field. It was recommended therefore that a reverse sequence of testing be adopted, in which selected plants should be tested in small cages with the agent at the critical host selection phase (e.g. oviposition or larval feeding), and then continue to test only those plants that were attacked and carry out the tests in less restricted conditions where some behavioural cues are required, and so on.

More recently, it has been suggested that selection of test species could be more reliably based on molecular phylogeny rather than taxonomic classification [113, 114]. Using a plant pathogen example, the potential for use of mixed model equations (MME) and best linear unbiased predictors (BLUPs) to estimate probable host-range and to construct plant test lists was demonstrated [115]. The equations can incorporate genetic relationships between potential host species, test data on the effects of the agent, and variances in effects between species, allowing predictions to be made for rare species that cannot be tested.

For biological control agents of insects, deciding upon a test species list has proved far more challenging for reasons described above. However, the general 'rule of thumb' has been to select test species with taxonomic and ecological affinities to the target pest [110, 116]. This case-by-case approach has been further developed by selecting test species from three categories, species with ecological similarities, species with phylogenetic/taxonomic affinities and 'safeguard' species (e.g. beneficial species, rare and endangered species, etc.) [74]. A novel, more objective approach, currently the subject of a 'proof-of-concept' investigation builds upon a method of test species priority ranking developed for risk assessment of genetically modified plants [88]. The principle of this approach is to construct a database of organisms in the receiving environment for the biological control agent, with detailed information which allows aspects of hazard and exposure to the biological control agent to be scored and analysed in a mathematical model. This model calculates an overall risk score and the organisms that rank highest can then be considered as high risk, and considered for inclusion in the test species list.

Once a test list has been decided upon, the selection of an appropriate test method is the next step. Again, there is a large body of literature debating the relative merits of various test methods. It has been argued that no-choice tests should be carried out to determine the physiological host range of a biological control agent [117], but recognizing that because of artificial 'cage effects' this probably does not accurately reflect the ecological host range, and often overestimates the likely field host range. Choice tests are considered by some researchers to be more realistic, providing information on host preference in a more natural situation. An established host/parasitoid system to determine the predictive accuracy of no-choice compared with paired choice tests was carried out in small laboratory arenas, and it was concluded that both were informative, but that in addition, detailed behavioural studies were also required [118].

Biosafety testing for weed biological control agents generally incorporates a range of behaviours (adult feeding, oviposition, larval feeding, development and survival, adult fecundity and host preference). Test methods have been reviewed by several authors [119–123]. For entomogenous biological control agents, it can be more difficult to determine 'physiological host range', because exposure of a test species to a parasitoid requires both a behavioural stimulation of the parasitoid to oviposit, and physiological immunosuppression to allow successful development of the parasitoid in a host. Rearing and dissection are normally used to estimate laboratory and field host range, and while molecular methods are available [124] to diagnose parasitism, it cannot always predict successful development.

Once all the available data have been collated and considered, a decision on whether or not a biological control agent should be released usually rests with regulators who are guided by legislation [36, 125]. A risk–benefit analysis is usually conducted [126] and the decision process varies depending upon how 'risk-averse' the legislation and regulatory process is in a particular country [35, 127].

Post-Release Monitoring and Retrospective Studies

Many studies have shown that non-target species can be attacked in the field by biological control agents which have been introduced, but attention has been drawn to the fact that a few studies have demonstrated that such attack has any impact on population density of a non-target species [128–130], especially in the case of parasitoids. A few biological control programmes have continued their efforts to the point where pre-release predictions were validated by post-release studies of biological control agents [104, 131]. From theoretical studies it was suggested that the impact on a non-target species would be greater if, in addition to sustaining a higher attack rate, it had a lower intrinsic rate of increase than the target, so clearly attack rates alone do not adequately describe risk to non-target species [63]. In practice, assessment for population-level impacts of biological control is very difficult, and rarely do biological control programmes obtain sufficient pre- and post-release population data to assess impacts on non-target species [132]. Non-target population impacts can be measured in several ways, including construction of population models
for non-target species, and then removing the biological control agent from the model [133, 134], or combining field experimentation with life-table analysis [135].

A meta-analysis carried out as part of the ERBIC study mentioned earlier found that 87 biological control introductions have led to recorded non-target effects, but that only 17 of these have involved population reductions [136]. By extrapolation of data from biological control introductions that have not been investigated post-release, the authors estimated that about 11% of all introductions may have had serious population consequences for non-target species. They concluded, however, that the most serious population impacts have resulted from polyphagous agents, which could have been predicted using host-range testing methods used today.

For weed biological control, the safety record appears to be very high, with only a few examples of species that have been released worldwide affecting non-target species at the population level. The best exception is the demonstrated impact of R. conicus attacking native North American thistle species mentioned earlier [84]. A retrospective study of weed biological control agents introduced into New Zealand showed that quarantine host-range tests had generally been appropriate, although some plant species had not been included in tests in some instances that in retrospect should have been [137]. Subsequent field surveys of the biological control agents most likely to have attacked non-target plants found, as predicted, that the cinnabar moth, Tyria jacobaeae L. (Lepidoptera: Arctiidae) has attacked some native Senecio spp. (Asteraceae). However, this was the only example found in the field of a weed biological control agent attacking a plant species native to New Zealand [138].

Studies that compare predicted risk with post-release realized effects can be very valuable for researchers and regulators. A summary of two workshops on identification of research needs for non-target impacts of biological control agents recommended that retrospective studies should aim to identify cases of significant non-target impacts; explore the mechanisms involved; evaluate host-range testing protocols; look at the circumstances under which changes in host-range occur post-release; and estimate population-level consequences of past releases [139]. A comparative retrospective case study was carried out with the parasitoids M. aethiopoides (Loan) and M. hyperodae (Hymenoptera: Braconidae), introduced for control of the lucerne pest S. discoideus Gylenhal (Coleoptera: Curculionidae) and the Argentine stem weevil, L. bonariensis (Kuschel) (Coleoptera: Curculionidae), respectively [140]. The approach used was to conduct laboratory host-range tests, predict the non-target host ranges from the results, and then validate the predictions with field data. The authors concluded that laboratory host-range testing was reasonably indicative of field host range [141].

In the future, it is likely that molecular technologies will increasingly be used to determine trophic interactions between organisms, and hence assist in investigating non-target impacts pre- and post-release of biological control agents [13].

Conclusion

Biological control is an invaluable tool for pest management, and the literature celebrates many examples of successful programmes. Risk assessment has increasingly become embedded in biocontrol programmes, and this has been beneficial not only for the safer implementation of weed and pest management but also for ecological theory. Prediction and interpretation of complex interactions between organisms, temporally and spatially in the ecosystem into which the agent will be released is enormously challenging, and the practice of biological control has evolved from a largely technical exercise to an opportunity to conduct research in a stimulating and rewarding field. Success rates will almost certainly improve in the future as a result of improved scientific rigour and greater investment of resources in each programme to assure both success in controlling the target as well as biosafety in the receiving environment. The literature that has accumulated over the last 20–30 years can go a long way towards helping define some useful principles by which a risk assessment can be conducted to minimize adverse environmental effects. It has become clear over this period that there are many stages in a biological control programme where information can be gathered, and, when compiled in a well-structured risk analysis, has enormous potential to reduce uncertainty.

Acknowledgements

I would like to thank many colleagues for their valuable insights and discussion over the years. This review was funded by New Zealand’s Foundation for Research, Science and Technology through contract CO2X0501, the Better Border Biosecurity (B3) programme (www.b3nz.org).

References


60. Wang XG, Messing RH. Newly imported larval parasitoids pose minimal competitive risk to extant egg-larval parasitoid of

http://www.cabi.org/cabreviews


http://www.cabi.org/cabreviews


95. De Nardo EAB, Hopper KR. Using the literature to evaluate parasitoid host ranges: a case study of Macrocentrus grandii (Hymenoptera: Braconidae) introduced into North America (to control Ostrinia nubilalis (Lepidoptera: Crambidae)). Biological Control 2004;31:280–95.


http://www.cabi.org/cabreviews
12 Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources


http://www.cabi.org/cabreviews