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BIOLOGICAL CONTROL OF WEEDS

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ABSTRACT

Classical biological control, i.e. the introduction and release of exotic insects, mites, or pathogens to give permanent control, is the predominant method in weed biocontrol. Inundative releases of predators and integrated pest management are less widely used. The United States, Australia, South Africa, Canada, and New Zealand use biocontrol the most. Weeds in natural ecosystems are increasingly becoming targets for biocontrol. Discussion continues on agent selection, but host-specificity testing is well developed and reliable. Post-release evaluation of impact is increasing, both on the target weed and on non-target plants. Control of aquatic weeds has been a notable success. Alien plant problems are increasing worldwide, and biocontrol offers the only safe, economic, and environmentally sustainable solution.

OVERVIEW

Biological control (biocontrol) of weeds has a long history and a good success rate (94). Biocontrol of weeds has followed a somewhat different track from biocontrol of arthropod pests: With weeds, host-testing is given greater importance, and classical biocontrol dominates over integrated pest management (IPM). Since earlier reviews of weed biocontrol appeared (25, 73, 169), techniques for assessing and evaluating risks have improved, but challenges to use of the approach have increased (88, 157).

Weeds are the most significant of the economic and environmental pests, and they are the target of much of the pesticides applied throughout the world. For example, herbicides comprise 47% of the world agrochemical sales, and

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insecticides 29% (172). Weeding, usually by hand, accounts for up to 60% of total pre-harvest labor input in the developing world (170). Invasive weeds cause enormous environmental damage, which is only now beginning to be recognized (see later section).

The literature on biological control of weeds is relatively compact. A complete list of all agents used worldwide is available (94), and an updated fourth edition will be published early in 1998 (95). The catalog is based on information supplied by weed biocontrol researchers; consequently, it is more complete than any compilation of published records, which are grossly inadequate in this field, as in many other areas of applied entomology.

Reports on current projects in the biocontrol of weeds are presented at the International Symposia on the Biological Control of Weeds, now held every three to four years. Julien (94) and the proceedings of the last three symposia (38, 39, 124) indicate who is active in biocontrol of weeds. For this reason, I do not list all programs of biological control of weeds worldwide; rather I concentrate in this review on issues and ideas of importance in the field.

Definitions

Nordlund (131) reviewed the different concepts of biocontrol as applied to weeds and insects and, in particular, the different "conceptual models" of biocontrol used by entomologists and plant pathologists. Following him, I use DeBach's 1964 definition of biological control as "the actions of parasites, predators, and pathogens in maintaining another organism's density at a lower average than would occur in their absence." This definition contains three different techniques for applied biocontrol: (*a*) "conservation"—protection or maintenance of existing populations of biocontrol agents; (*b*) "augmentation"—regular action to increase populations of biocontrol agents, either by periodic releases or by environmental manipulation; and (*c*) "classical biocontrol"—the importation and release of exotic biocontrol agents, with the expectation that the agents will become established and further releases will not be necessary. Classical biocontrol is the mainstay of weed biological control; conservation is hardly used (74). Augmentation is used with mycoherbicides and some insects, as well as by the deliberate use of grazing animals for weed control (143).

Augmentation Using Pathogens

An extensive literature on potential bioherbicides exists, almost entirely about fungi, but there is little actual use of these as commercial or practical methods in the field (125). Particularly in the United States, weed scientists often use the term biocontrol to refer solely to the use of pathogens as mycoherbicides, ignoring the existence of classical biocontrol (7, 145). However, only three mycoherbicides have ever been registered and used commercially—

DeVine (*Phytophthora palmivora*), Collego (*Colletotrichum gloeosporioides* f. sp. *aeschynomenee*), and BioMal (*Colletotrichum gloeosporioides* f. sp. *malvae*). All were subsequently withdrawn for commercial reasons (79, 125). A Japanese company is launching three new mycoherbicides against rice weeds and for golf course turf [*Biocontrol News Inf.* 17(4):62N, unpublished data]; it remains to be seen if these will be commercially viable. Research continues on many potential bioherbicides, but problems with mass-production, formulation, and commercialization continue to prevent their use (4, 125). As practical, economically viable alternatives to chemical or mechanical weed control, bioherbicides are still unproven.

Augmentation Using Insects

Few examples exist where native insects are artificially increased or otherwise manipulated for the control of native weeds (86, 94, 142). Manipulation of introduced biocontrol agents is more widely used, when the agent dispersal capacity is poor and the weed occurs in discrete scattered areas. Cacti in Australia and South Africa are controlled through the regular redistribution of mealybugs into isolated infestations (87, 123). In Australia, the floating fern salvinia (*Salvinia molesta*) is controlled in ponds and other water bodies by the release of the weevil *Cyrtobagous salviniae* supplied in bags of infested salvinia (R Wood, personal communication). The management of water weeds in the United States relies heavily on the manipulative use of biocontrol agents, and special information packages have been developed to train operational personnel in the procedures (66).

CLASSICAL BIOLOGICAL CONTROL

Legislation

Classical biocontrol depends on the introduction of exotic insects and pathogens and as such is subject to legislative control. The current system in Australia was well reviewed by Paton (137). Two acts apply: the Quarantine Act, designed to keep out diseases and agricultural pests, and the Wildlife Protection Act, designed to control trade in endangered wildlife. Issue of permits is administered by the Australian Quarantine Inspection Service (AQIS), following protocols developed over the years, and with applications reviewed by scientists in each of the eight Australian states and territories. The Biological Control Act of 1984, designed to deal with conflicts of interest such as that over Paterson's curse, *Echium plantagineum*, provides a legal basis for introduction of control agents (34, 74). Unfortunately, review procedures under the act are protracted and onerous, and the act was not invoked until the introduction of calicivirus to control rabbits in 1996 (137; G Maynard, personal communication).

Legislation in Canada and the United States was reviewed by Harris (74). Introduction of biocontrol agents is controlled by the Federal Plant Pest Act of 1957 in the United States and the Plant Protection Act of 1990 in Canada. Both acts were designed to prevent introduction of insect pests of plants, with the interesting result that weed biocontrol agents became “beneficial pests”! As in Australia, the legislation was written in broad terms, and therefore the regulations and guidelines applied by the US Department of Agriculture and by Agriculture Canada are important in practice.

In countries where weed biocontrol is infrequently practiced, the lack of any agreed protocols for introductions or any defined authority to grant permits can be a major problem, particularly where classical biocontrol of arthropods is also rare. Usually weed biocontrol can follow the procedure existing for insect biocontrol, as in Indonesia (S Tjitrosoedirdjo, personal communication). In Britain, determination of who could authorize the release of agents against bracken was a problem (SV Fowler, personal communication). The United Nations Food and Agricultural Organization (FAO) has developed the International Code for the Import and Release of Exotic Biological Control Agents (101). By clarifying procedures and responsibilities, the code, approved by member states in 1995, is particularly helpful for countries without a tradition of biocontrol.

Countries Actively Involved

The five most active countries, rated by numbers of weed species targeted and agents released, are the United States, Australia, South Africa, Canada, and New Zealand, with the United States and Australia nearly twice as active as the others (Table 1). All these countries have a long history of successful weed biocontrol. Programs have been reviewed by Goeden (59) for the United States, Harris (74) for Canada, Bruzzese & Cullen (14) for some projects in Australia, and Hoffmann (81, 82) for South Africa. Significant

Table 1 Number of agent species released and weed species targeted by 1990 in the five most active countries [adapted from Hoffmann (82)]

Country	Agent species released	Weed species targeted
United States, including Hawaii	130	54
Australia	123	45
South Africa	61	28
Canada	53	18
New Zealand	24	15

cooperation occurs between the United States and Canada and between South Africa, Australia, and New Zealand in addressing common weed problems. For foreign exploration, all countries have used the International Institute of Biological Control (IIBC) (58, 94, 114), and all except Canada also undertake their own exploration programs, with scientists based overseas for varying periods (5, 10, 62, 71, 114, 153). Pathogens as well as insects are increasingly used by all major countries (13, 48, 56, 85).

Other countries involved in classical biocontrol are Malaysia (134), Thailand, India (78), Indonesia, Vietnam, Papua New Guinea, and China. Active biocontrol projects occur in Africa (Uganda, Zambia, Tanzania, Kenya, Ghana, Côte d'Ivoire, and Benin) and in South America (Argentina and Chile) (95, 97).

Apart from unsuccessful releases of the chrysomelid *Altica carduorum* against Canada thistle, *Cirsium arvense*, in the United Kingdom, the only releases of biocontrol agents against weeds in Europe were in the former USSR (94, 148). No agents were released in the biological control program against bracken in Britain (50; SV Fowler, personal communication). Recent initiatives have been made towards biocontrol of some crop weeds in Europe (127).

CHOICE OF TARGET WEEDS

Probability of Success

Decisions on whether weeds are suitable targets for biocontrol programs are based on the benefits to be achieved plus estimates of the probability of success (139, 169). The more widespread and damaging the weed, the greater the potential benefits, but these may be hard to quantify for environmental weeds (10, 52, 71). Estimating the probability of success in a biocontrol program depends on a number of difficult-to-predict factors. Successful biocontrol depends on three main variables: the damage each individual agent can do to the plant; the ecology of the agent, which determines the population density achieved in the new environment; and the ecology of the weed, which determines whether that total damage is significant in reducing its population (33). The first is relatively easy to determine; the problem is predicting the other two. Untested theories may become established dogma and adversely affect the decisions made (17). Biocontrol of trees has been believed to be particularly difficult, yet there are several examples of tree populations controlled by insects (42, 107). Classical biocontrol has been seen as unsuitable for weeds of annual crops or other frequently disturbed environments (46, 148), yet there are examples of successful control of crop weeds (19, 110, 126). Plants that reproduce sexually were judged hard to control because of their genetic variation (16), but further analysis showed this to be untrue (17).

All authors agree that successful biocontrol in one country greatly increases the chances of success in another (139), though there are examples of successful control in one country and failure to control the same weed using the same agents in other countries (27, 98, 99, 173). Prior use elsewhere also reduces the cost of a biocontrol program, as the expensive overseas surveying and testing are already completed (20, 45). Probability of success may be reduced where the weed has close relatives of economic or conservation value because agents that are selected must be monophagous, which is comparatively rare (132). However, pathogens are often specific to a single plant species or even strain (48, 76).

Conflicts of Interest

Serious conflicts of interest that arise from consideration of a plant as a weed in one situation and a valued plant in another may prevent the use of biocontrol (56, 73, 74). Special legislation may be required to remove the right of the damaged party to sue and to provide for compensation for financial loss from control of the plant (34). Where a plant is a serious weed in natural ecosystems but is valuable in other contexts, payment of compensation may be an acceptable solution if the economic value of the plant is minor, for example, strawberry guava, *Psidium cattleianum*, and ginger, *Hedychium gardnerianum*, in Hawaii (56). Where the economic value is great, biocontrol may be inappropriate [for example, the *Pinus* spp. used for forestry are considered major environmental weeds in several countries (149)]. Restricting programs to the use of seed predators to reduce spread may be an acceptable alternative (42).

Another conflict of interest involves native plants that are of conservation value but may be serious weeds of agriculture or grazing land (40, 74). A program to control bracken, *Pterididium aquilinum*, in the United Kingdom (50) was abandoned after extensive agent testing because of requirements for costly field cage tests and doubts over the wisdom of biocontrol of a native weed (SV Fowler, personal communication). On the other hand, insects from South America have been released in the United States to control the native snakeweed *Gutierrezia* spp. (40), and introduced insects were used against native *Opuntia* spp. in both the United States (60) and the West Indies (158).

Conflict over biocontrol of alien weeds in natural ecosystems may arise from concern with maintaining or reestablishing the indigenous ecosystem. Replacement of native vegetation by alien plants may favor some native animals, and biocontrol may be opposed for fear that it will leave the native animals without essential resources. Black cockatoos in the wheat belt of Western Australia are now dependent on seed of the introduced weed *Emex australis*, and concern over this delayed the release of biocontrol agents (J Scott, personal communication). Where salt cedar *Tamarix* spp. has replaced native *Salix* spp. in the United States, endangered birds use the salt cedar for nesting; biocontrol permits were refused for fear that the birds would be left with nowhere to nest or feed (41). In practice, successful biocontrol never eradicates the target weed and usually takes 10 or more years, during which time native vegetation can gradually replace the alien plant (161).

PROCEDURES

The steps involved in a weed biocontrol program (70, 169), after the initial decision that classical biocontrol is appropriate, are overseas exploration (58); selection and testing of agents (168); rearing and release; and evaluation. Overseas exploration requires correct identification of the weed and its country of origin, which is not always straightforward (58, 169). Genetic analysis, based on specific plant chemicals (85), isozymes (102), and DNA (122, 130), is being used to identify and characterize the different strains of a weed and to facilitate the collection of agents from the same strain and place of origin as the target weed. This is particularly important for pathogens that are often strain-specific (48, 76).

Agent Selection

Agent selection is the critical step, and the choice of the best agent is the “holy grail” of weed biocontrol. On average, each agent tested and introduced requires three scientist-years (73, 152), which, with technical support and facilities, cost about $460,000 in 1997. Because the investment in each agent released is substantial, there is economic pressure to choose the most appropriate agents. Also of importance is assurance that the risk involved in introducing any new agent (see later section) is justified by its potential contribution to successful control (32).

Many theories or protocols have been proposed for choosing the best agent, based on either post-hoc analyses of reported results or on pre-release studies of agent impact in its native range (8, 33). Post-hoc analyses, often from Julien’s catalog (94), suffer from the lack of objective criteria regarding “success” in control achieved, or even in agent establishment (26, 27, 32, 33, 168). The theory of “new associations” claimed that the success rate was higher for agents collected from plants other than the target weed than for agents that had “coevolved” with the plant (84); however, this was disputed (61), and the theory is now generally abandoned. Another theory proposed that the introduction of several agents could lead to reduced control through competition (47); this has been disproved, in practice as well as in theory (8, 10, 67). Protocols for agent selection, although useful discussion points, are of little or no predictive value (152), partly because success does not depend on the biology of the insect as much as on its interaction with environmental factors such as climate and parasites or predators (8, 58). Sometimes the “best” agent proves to be not as good as predicted (98, 173), whereas in other cases agents perform better than expected (83, 117).

Predictions based on pre-release studies of agent impact in their native range (8) may prove equally useless, chiefly because predicting the factors affecting agent populations in the new country is impossible (98, 117). Predictions based on climatic analysis need to be treated with caution (118) because the best climatic match is no guarantee of success, whereas some agents have thrived outside their "normal" climatic range (58, 116). In extreme climates such as Canada, however, climate matching may be of greater importance (113).

Host-Specificity Testing

The necessity for detailed host-specificity testing of all agents before field release has been an accepted doctrine since the biocontrol of prickly pear (44). This approach is quite different from that generally used in arthropod biocontrol, in which host testing of parasites or predators before release only began in Australia in the 1980s and is still not customary in many countries, including the United States (88). Tests of feeding preference are commonly performed on all mobile stages (adults and mobile larvae or nymphs). Where larvae cannot move between plants, adult oviposition choice is tested instead. Because oviposition in itself does not usually cause significant damage, the critical factor is the ability to feed and develop on the test plants (9, 31, 112, 167). Test results for acceptable agents are published, but, with some exceptions (120, 135), results for rejected agents are often not published, giving the impression that potential agents are never rejected.

Host-specificity test lists have progressed from long lists of crop plants unrelated to the normal host to targeted lists of plants closely related to the weed and including native species (49, 119, 120, 167). The aim is no longer to demonstrate that a group of valued plants will not be attacked, but rather to determine the potential host range of the agent and therefore which plants if any will be at risk in the field (9, 31, 112, 167). An understanding of host specificity is greatly improved when the insects attacking a complete taxonomic group of plants are known (11, 62, 114, 155) or where the host relationships of a taxonomic group of insects is studied (2, 54). Developing theories on the evolution of host specificity are having an impact on the understanding of host range. Evolution in phytophagous insects is now generally agreed to have been from generalists to specialists, with a progressive loss of genetic variation in ability to use different host plants for oviposition or feeding (54). Thus, highly host-specific insects introduced into a new country are most unlikely to become selected for ability to use novel plants as hosts (108).

Interpretation of results of host-specificity tests poses some problems, which are discussed in detail by Cullen (31). So long as the insects tested are from the same population as that to be released, are healthy and physiologically ready to feed (e.g. not in diapause), and are provided with suitable plants, then negative results, i.e. failure to feed on the test plants, are conclusive (31). The major problem encountered by biocontrol researchers is the interpretation of results in which feeding on non-target plants occurs in tests but not in the wild. Such feeding may be an artifact of confinement, whereby restriction in cages prevents normal host-finding behavior (5, 75). Use of larger cages and more natural conditions may result in more normal behavior and more genuine results (31, 119). However, sometimes it is the field data that is inadequate (135). If extensive development or feeding occurs in laboratory tests on plants that are not attacked in the country of origin, very careful analysis is needed to determine whether other factors, such as specialized pupation requirements (5) or aggregation responses to chemicals from the damaged plant (166), might prevent attack on these plants under field conditions. If no such limiting factors exist, then it must be assumed that attack will take place (119).

Open-field testing in the country of origin allows the insect to show its full range of behavior (12, 21). The weakness of the method is that agent populations, and hence feeding pressure, are typically low and may be much lower than potential populations in the new country (58). Testing must take into account the possibility that very high population levels developing on the host weed may result in starving insects dispersing onto adjacent crop or other plants (31), causing significant damage even if development or long-term survival is not possible (see below). For this reason, non-choice tests on closely related at-risk plants must be part of the testing schedule (167).

Host testing can never give absolute answers, i.e. guarantee the agent will never attack other plants, but it provides the information required for a process of risk assessment (9, 112). When test results indicate attack will occur on desirable native or crop plants, the decision whether or not to release the agent is ultimately political, based on weighing the risks of release against the consequences of alternative control methods. Agents have been released with the knowledge that they would attack non-target plants, where the relative value of the non-target plant was significantly lower than the damage (economic or environmental) caused by the weed (119, 132). In such cases, resources must be allocated for careful evaluation of the ultimate impact on both weed and non-target plants.

Evaluation

Evaluation of biocontrol programs is essential to justify continued expenditure (10). In the past, there has been little follow-up evaluation of biocontrol programs (8), chiefly because financial sponsors took the view that it was unnecessary. As a result, the criticism by opponents of biocontrol, that there has been little evaluation of the impact of biocontrol agents on nontarget organisms (88), is unanswerable—there has also been little evaluation of the impact on the target weed itself!

The first step in evaluation of the impact of biocontrol is pre-release studies of the weed in the target country (140), but too often these are not done (117). Examples of good pre-release studies are those on *Mimosa pigra* in Australia (106), *Cynoglossum* spp. in Canada (36), and *Chrysanthemoides* spp. in Australia and South Africa (153).

Most evaluation is undertaken after agent release and establishment, but it may be limited to monitoring the presence and spread of the agents, without evaluation of impact on the weed and its population dynamics (111). Laboratory experiments may demonstrate that insect feeding significantly affects the plant, but the relevance to weed population dynamics may not be established (26, 159).

Impact of biocontrol can be determined experimentally in the field by excluding the agent(s) artificially by insecticide or exclusion cages. Such experiments have been few (26), mainly because of the requirement for long-term treatment with insecticides or maintenance of cages, but increasing numbers of experimental studies are now published (105, 115, 154). Long-term experiments are the most valuable but are difficult and expensive. For example, because of residue problems, farmers are unwilling to graze cattle on plots treated with residual insecticides, and cages exclude cattle as well as insects. Grazing effects then have to be artificially reproduced. Nevertheless, these difficulties can be overcome, especially where universities incorporate evaluation studies into their post-graduate research program (128). A major evaluation project on scotch broom (*Cytisus scoparius*), financed by the Leverhulme Unit, United Kingdom, involves large-scale field experiments and surveys in its native range (United Kingdom and France) and in New Zealand and Australia where it is a weed; the project will determine the factors affecting the population ecology and invasiveness of the weed in the two areas (52).

Post-establishment analyses to determine reasons for success or failure may help develop our understanding of biological control (126) but do not necessarily lead to improved practical biocontrol. Evaluation of the unsuccessful control of the thistle *Carduus nutans* in New Zealand, 20 years after releases, demonstrated that a high level of seed destruction by the biocontrol agent has minimal impact on the population dynamics of the weed in New Zealand, in contrast to Canada and the United States (99). However, still no clear understanding of the reason for these differences exists, and the only prospect for improved biocontrol remains the introduction of new agents attacking other life stages of the plant. Models, validated against experimental results, are increasingly under development to test the theoretical framework of biocontrol and to predict field impact of damage from biocontrol agents (80, 105). Simple models that exclude effects such as pasture competition and density-dependent intraspecific competition may, however, be of limited value (128).

RESULTS ACHIEVED

Successes and Failures

Consideration of successes is bedevilled by the problem of assessment—when is control "successful"? A major weakness in Julien's catalog (94), and thus in all analyses based on it (25, 33), is that the degree of success claimed is subjective and varies between sources. I propose that we adopt Hoffmann's (82) definitions for success: (*a*) "complete," when no other control method is required or used, at least in areas where the agent(s) is established; (*b*) "substantial," where other methods are needed but the effort required is reduced (e.g. less herbicide or less frequent application); and (*c*) "negligible," where despite damage inflicted by agents, control of the weed is still dependent on other control measures. Complete control does not mean the weed is eradicated or is no longer an important component of the weed flora, but it indicates that control measures are no longer required solely against the target weed and that crop or pasture yield losses can no longer be chiefly attributed to this weed (19, 115). Substantial control includes cases where control may be complete in some seasons and/or over part of the weed's range.

Post-hoc analyses of success suffer from the inclusion of data from recent programs before equilibrium has been reached. Because agent establishment may take many years (REC McFadyen, unpublished data; 165) and control up to 10 years after that (82), analyses of success rates should be based only on programs in which 10–20 years have elapsed since the last introduction.

In many published analyses, confusion exists between success rates of individual agents and success for programs as a whole. Rates are generally quoted as successful establishment of 60% of agents introduced, with 33% of these resulting in control (25, 27, 171). More important is the proportion of programs that achieve successful control. In South Africa, 6 weeds out of 23 targeted are under complete control, and a further 13 are under substantial control, which gives a success rate of 83% (82). In Hawaii, 7 weeds out of 21 are under complete control, and substantial control has been achieved for 3 more, giving a success rate of nearly 50% (56, 109). Expectations that the weed must be completely controlled cause partial successes to be counted as failures, so that the very real savings achieved are not measured or recognized (82). Similar analyses are not available for Australia, the United States, and Canada, but success rates are probably in the same range.

In early programs, very small releases of control agents were often made, and establishment rates were consequently poor. Agents are now released in larger numbers, often with the initial use of field cages, and there is more redistribution of established agents (10). Establishment rates are approaching 100% for some programs (71), and the increased effort devoted to agent distribution may also reduce the lag time between establishment and successful control. There is always a conflict between making many small releases to "spread the risk" and making fewer larger releases to increase the viability of initial populations. Ecological theory can help determine the optimum release size for establishment with different agents (65). Analysis of past releases can improve understanding of the factors involved in successful establishment (77).

For a complete list of successes and failures, the reader should turn to Julien (94, 95), with due caution regarding the results of recent programs. Major successes in the last two decades include tansy ragwort (*Senecio jacobaea*) in the United States (115) and nodding thistle *C. nutans* in Canada and the United States (53, 72). Biocontrol of aquatic weeds has been a series of major successes: water hyacinth, *Eichhornia crassipes* (67, 97); the floating fern salvinia (150, 162); and water lettuce, *Pistia stratiotes* (18, 69). Control of the submerged weed *Hydrilla verticillata* in Florida shows every indication of success (22). Alligator weed (*Alternanthera philoxeroides*) has been successfully controlled in most countries in its aquatic phase though not when growing on land (96).

Less well-known examples are the successful control of the following: *Cordia curassavica* in Malaysia after the earlier success in Mauritius (134); the annual weed Noogoora burr, *Xanthium occidentale*, in Australia (19, 126); Harrisia cactus, *Eriocereus martinii*, in Australia (117); and *Mimosa invisa* in Australia and Papua New Guinea (1, 100). The perennial shrub *Chromolaena odorata* has been successfully controlled in the Marianas (156) and now in large areas of northern Sumatra (R Desmier de Chenon & A Sipayung, unpublished data). The perennial shrubs Hamakua pamakani, *Ageratina riparia*, and Klamath weed, *Hypericum perforatum*, are now under complete control in Hawaii (56, 109).

A notable continuing failure, where well-resourced programs have failed to achieve sufficient control, has been lantana (*Lantana camara*) over most of the tropics except Hawaii. Using the criterion of agent establishment, lantana was rated as successfully controlled on 21 occasions (25), yet in many countries it remains a major weed (160), and the biocontrol programs in most countries must be regarded as failures.

Economic Benefits

Economic evaluations of weed biocontrol programs serve two purposes: Economic evaluations undertaken prior to the program can be used to determine allocation of funds to biocontrol programs (35, 64), and analyses after the program is complete are undertaken to demonstrate the value of the method. Despite the obvious problems associated with prior estimates of probability and timing of successful control, these are already incorporated into applications to funding bodies in Australia (Cooperative Research Centre for Tropical Pest Management, unpublished data). Analyses of this kind, which show massive potential benefits from biocontrol of blackberry, *Rubus fruticosus*, and Paterson's curse, *E. plantagineum*, in Australia, were used to justify biocontrol programs where there was conflict over the value of these plants to agriculture (35). Unfortunately, most such economic analyses are not published nor reanalyzed once the program is completed.

Post-program economic evaluations of classical biocontrol, for both arthropod and weed pests, have been recently reviewed for Australia (35). The successful biocontrol of Noogoora burr in Queensland resulted in annual benefits (in 1991) of $720,000, a return of 2.3:1 (19). Evaluations of the successful control of skeleton weed (*Chondrilla juncea*) (110) and of tansy ragwort (24) have demonstrated benefit-cost ratios of 112 and 15. An evaluation of the control of salvinia in Sri Lanka by the weevil *C. salviniae* gave an amazing benefit-cost ratio of 1675 (45)—an example where costs were low because the weevil had already been tested and used in Australia. Biocontrol programs also result in substantial non-economic benefits, in sustainability of the success, and in equity, in that benefits are not limited to those who can afford the product. Costs are the risk of failure and possible damage to non-target species (35).

Both benefits and costs are particularly hard to determine for environmental weeds, where agricultural costs are not involved (35, 52). The program against *Passiflora mollissima* in Hawaii cost about $1 million over 5 years, and further expenditure may be required (109). This amount is small compared with costs of herbicide control, but it may be large in relation to budgets for management of natural ecosystems.

Damage to Non-Target Plants

Concern over damage to non-target organisms is emerging as one of the major challenges to biocontrol, of weeds as well as of arthropod pests. Critics quote examples taken almost exclusively from biocontrol of arthropods but include weed biocontrol in the negative statements that they make (88, 157). Comments such as "...notable disasters where organisms were introduced to control weeds with little regard to non-target organisms" are made without examples or references (30). The only non-specific agents used in weed biocontrol have been fish, introduced decades ago into several countries primarily for fishing and sport (94, 164), with frequently disastrous results. In preparation for this review, therefore, I contacted biocontrol, weed, and exotic pest newsgroups on the Internet, requesting examples of weed biocontrol agents causing damage to non-target plants anywhere in the world. All examples obtained from this and from the literature are listed in Table 2.

In the first five examples, the host range of the agent was known at the time of release to include genera containing plants native to the country of introduction, but attack on native plants of no economic value was not then seen as a problem. *Cactoblastis cactorum* in the Caribbean is a somewhat different example in this category (6). When it was introduced into the West Indies in the late 1950s to control the native cactus *Opuntia triacantha*, no value was placed on native cacti, and neither conservationists nor the US government raised objections when the results were published (158). The moth has since spread throughout the Caribbean, both naturally and through deliberate introductions, until in 1989 it was found in the Florida Keys (138). Here it is threatening the survival of native *Opuntia* spp. that are already endangered by clearing and development of the Keys, which had reduced *Opuntia spinosissima* to 12 small patches in a national park (93). *C. cactorum* is likely to continue its spread westward into Mexico and the cactus country of the southwest United States (157), where its impact may be severe unless it is reduced by the effects of parasitism or by competition with similar native moths in the genus *Melitara.*

With the two lantana insects, only limited testing was carried out prior to release in Hawaii, and scientists in Australia and Africa relied on the field results from Hawaii (68). In the last example, attack on sunflower by the beetle *Zygogramma bicolorata* was not anticipated, despite test results showing that starving beetles will feed on sunflower (121), because of failure to appreciate the impact of very large beetle populations in the initial years of establishment (147). As the weed becomes less abundant, the problem is subsiding (91). In all examples, economic losses have been very minor and/or temporary, and they are far outweighed by the benefits obtained. Environmental damage is harder to assess, and in most cases it has not been properly evaluated. Damage by the agents must be weighed against the benefits from control of these widespread introduced weeds and from the cessation of chemical use over extensive areas of grassland and natural vegetation.

FUTURE OF WEED BIOLOGICAL CONTROL

Increase in Alien Weed Problems

From the start, the introduction of weed biocontrol agents has been strictly controlled and has required evidence that the agents will not damage non-target organisms. Unfortunately, this is not true of the transport of other organisms around the world. Of the plant and animal species deliberately introduced into the United States for agriculture, sport, or as pets, respectively 2%, 50%, and 50% have become pests (141). Plant introductions for forestry and pasture have increased greatly in the last three decades, which will inevitably lead to

Table 2 Worldwide recorded instances of damage to non-target plants by biological control agents

Target weed	Agent	Released	Non-targets attacked	Anticipated?	Damage	References
Senecio jacobaea ragwort (Asteraceae)	*Tyria jacobaeae* cinnabar moth	Canada and United States, 1959–1963	*Senecio triangularis*; *Senecio integerrimus*	Yes	Not assessed or minimal	15, 43; D Isaccson, personal communication
Rubus argutus blackberry (Rosaceae)	*Croesia zimmermannii* leaf-roller moth	Hawaii, 1964	*Rubus hawaiiensis*	Yes	Not significant	55
Hypericum perforatum Klamath weed (Clusiaceae)	*Chrysolina quadrigemina* chrysomelid beetle	California, 1946	*Hypericum calycinum*	Yes	Marginal	3
Carduus spp. thistles (Asteraceae)	*Rhinocyllus conicus* seed weevil	United States, 1969	*Cirsium* spp.	Yes	Not known	163; AS McClay, personal communication
Opuntia spp. prickly pears (Cactaceae)	*Cactoblastis cactorum* internal feeding moth	Caribbean, 1957	*Opuntia* spp.	Yes	Significant to endangered species	6, 138, 158
Lantana camara lantana (Verbenaceae)	*Uroplata girardi* chrysomelid leaf miner	Hawaii, 1961 Australia, 1966	*Ocimum basilicum*, basil and other herbs (Labiatae)	No	Minor	23; BW Willson, personal communication
	Teleonemia scrupulosa lace bug	East Africa, 1962	*Sesamum* spp.	No	Minor	63, 68
Parthenium hysterophorus parthenium weed (Asteraceae)	*Zygogramma bicolorata* chrysomelid beetle	India, 1984	*Helianthus annuus*, sunflower	No	Minor	92, 121, 147

increased weed problems after a lag time typically of 50 years (89). Of "pasture" plants introduced into northern Australia, 13% have become weeds (104). Because of the characteristics for which these plants are selected—ease of establishment, rapid growth, high competitiveness—such introductions are more likely to become invasive weeds. The nursery trade is another problem; most pernicious weed species in the United Kingdom were deliberately introduced as garden ornamentals (28), as were 85% of woody plants invading natural areas in the United States (146). Unlike biocontrol agents, these plant introductions are not subject to any controls in most countries (89, 136).

To compound the problem, damage caused by alien plants to natural ecosystems has been under-researched, and its full seriousness not appreciated (30). Alien plant invasions can alter the primary production level and the vegetation structure (29), and whole ecosystems can be destroyed, perhaps irreversibly. For example, increased transpiration by salt cedar *Tamarix* spp. drained all surface water from a California freshwater marsh (129). Invasion of beaches by *Casuarina equisetifolia* in Florida prevents nesting by endangered American crocodiles and sea turtles (103). A recent study in South Africa demonstrated reduced invertebrate species diversity in areas invaded by alien woody weeds as compared with diversity in the native vegetation or even in plantation forests (151). The disastrous impact of invasive weeds on native ecosystems has been recently reviewed for the world as a whole (30), for the United States (144), and for Australia (90).

Alien plant invasions now affect conservation areas on every continent except Antarctica (29). As a result, conservation scientists and managers are increasingly accepting that "biocontrol is the only resort when the invasion is 'out of control"' (29, p. 10; 30), but this understanding has not reached the general conservation community or the public as a whole. Biocontrol of weeds of environmental areas faces difficulties in assessing damage caused, when economic loss is no longer the sole criterion, and in working with different interest groups and financial sponsors (51). However, despite these problems, well-funded programs against nonagricultural weeds are in development (10, 71).

Biocontrol may be the only feasible solution to many of these weed problems. Practitioners need to ensure that the science is rigorous and test methods appropriate. The scientific community needs to ensure that when test results are clear and satisfactory, biocontrol is not hamstrung by unnecessary regulation, fear, or confusion with other issues such as genetic technology. Some conservation groups, for example an early opinion by the Australian Conservation Foundation (quoted in 35), would prohibit any introductions of new biocontrol agents (insects or pathogens) until all potential effects of the introductions are known. Because of the complexity of natural ecosystems and food webs, this would effectively prevent any further introductions and bring classical biocontrol to a halt and, for this reason, is not generally supported (88, 157). The FAO now regards biocontrol of weeds as an option to be promoted and is currently supporting programs for the biocontrol of water hyacinth in Latin America and Africa, itchgrass (*Rottboelia* spp.) in Central America and the Caribbean, *C. odorata* in West Africa, and the parasitic weeds *Orobanche* and *Cuscuta* species in North Africa (101).

Weighing the Risks

Despite the long history of successful and safe biocontrol of weeds, practitioners do need to recognize the risks involved. Classical biocontrol is irreversible—an agent once widely established in a new country cannot be eradicated—and therefore it is essential that all potential consequences are adequately considered beforehand. Successful biocontrol agents may disperse far beyond the original target area, e.g. lantana seed fly in southeast Asia (133) and *C. cactorum* in Florida (6, 138), and their impact in their full potential range must be considered. On the other hand, those who oppose releases until all possible consequences are understood, in effect indefinitely, need to remember that the uncontrolled growth of weeds is already causing environmental damage and species extinctions, which will continue so long as control is delayed.

Classical biocontrol involves a process of decision analysis—balancing the risks of releasing versus the risks of no control (9, 112). Accurate prediction of the potential host range of the agent minimizes the risk. Practitioners need to consider the full range of issues involved: the importance of non-target plants and associated fauna; the probable impact of any damage; and probable damage to non-targets from other control options, including no control. Decisions must be made by appropriate public bodies after an open process: The role of biocontrol scientists is to submit proposals and supply information but not to make the final decision. Resources have to be provided for long-term post-release monitoring of impacts on both target and non-target species (88). Both supporters and opponents of classical biocontrol need to recognize that, in the context of alien invasive weeds, doing nothing is not "benign neglect" (157); rather, it allows the environmental and economic damage to continue and to increase unchecked. If legal biocontrol using appropriate channels is made too difficult, expensive, or slow, individuals or groups who are suffering economic losses from the weeds may act outside the law, with enormously increased risk of undesirable side effects (88). In Australia alone, two examples of clandestine introductions occurred that were both almost certainly a result of blocks in the legal procedures (13, 126).

Conclusions

Biological control of weeds using imported insects and pathogens is safe, environmentally sound, and cost effective. The successes listed earlier have already saved many millions of dollars in control costs and increased production.

Control of the water weeds salvinia and water hyacinth has preserved the life style of entire communities as well as restored biodiversity to destroyed aquatic ecosystems. In contrast, after nearly 100 years of use, there are only eight known examples of damage to non-target plants, none of which have caused serious economic or environmental damage. Invasive weeds are as environmentally damaging as land clearing, but their attack is more insidious because the loss of native species, both flora and fauna, is not obvious unless these effects are measured (151).

Future plant introductions should be subject to the same level of control as biocontrol agents, but meanwhile we can expect a massive increase in invasive weed problems as the plants introduced over the last 50–100 years become naturalized and begin to spread. Classical biocontrol must be available to control these weeds. Mechanical or cultural control is not feasible in natural ecosystems, and widespread use of herbicides is economically unsustainable and unacceptable on environmental and health grounds. Classical biocontrol is the only safe, practical, and economically feasible method that is sustainable in the long term, and the importation of insects and pathogens must not be prevented by ever-increasing restrictions and demands for pre-release studies. These demands are usually fueled by unrealistic fears, based on misquoted or out-of-context examples, and on a misunderstanding of host restriction in highly host-specific insects and pathogens. To claim that no risks are involved would be irresponsible, but these risks are small and must be weighed against those of alternative control methods, in a context in which ecosystems and livelihoods are being destroyed and neglect is not "benign."

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