Status of biological control in vegetation management in forestry[1]

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Biological control traditionally depends upon importing the natural enemies of introduced weeds. Since vegetation management in forestry has primarily been aimed at protecting economic species of trees from competition from other native plants, biological control has been of little use in forestry. An alternative approach to controlling unwanted native plants, supplementing their existing complex of natural enemies with introduced insects found attacking closely related plants, is being used on rangeland, but is not recommended for forestry. New agents will not remain restricted to the location where they are released, but will spread and would eventually affect the target plant throughout its entire range, including areas where it might be desirable. A more promising alternative is manipulating one or more insects or diseases that already attack the undesirable plants. Many plant pathogens naturally associated with a particular plant species are highly virulent and specific to only the target plant. Mass producing these pathogens and applying them with conventional spray systems is being used in agriculture and is being considered for forestry. Other methods of manipulation, such as mass rearing insects and releasing them to attack the undesirable plant or manipulating populations of the insect predators that naturally suppress phytophagous insects of a target plant, are discussed.

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Traditionnellement, le contrôle biologique a reposé sur l'importation d'ennemis naturels des mauvaises herbes introduites. En foresterie, le contrôle biologique a été peu utilisé étant donné que le contrôle de la végétation a surtout été orienté vers la protection des espèces d'arbre qui ont une valeur économique contre la compétition par d'autres espèces indigènes. Une approche alternative, utilisée pour le contrôle des plantes indigènes indésirables et qui consiste à ajouter des insectes introduits, qui s'attaquent à des plantes apparentées, à leur complexe existant d'ennemis naturels, est utilisée pour les pâturages mais cette pratique n'est pas recommandée en foresterie. Les nouveaux agents de contrôle ne seraient pas confinés aux endroits où ils ont été relâchés mais se disperseraient et affecteraient éventuellement la plante cible partout dans son aire de distribution, incluant des endroits où on pourrait vouloir conserver cette plante. Une alternative plus prometteuse consiste à manipuler un ou plusieurs insectes ou maladies qui s'attaquent déjà aux plantes indésirables. Plusieurs organismes pathogènes des plantes, naturellement associés à une espèce de plante en particulier, sont très virulents et spécifiques seulement pour la plante cible. La production massive de ces organismes pathogènes et leur application au moyen de systèmes conventionnels de pulvérisation est une méthode utilisée en agriculture qui est envisagée pour la foresterie. D'autres méthodes de manipulation, comme l'élevage en masse d'insectes et leur relâchement pour qu'ils attaquent une plante indésirable, ou la manipulation des populations d'insectes prédateurs qui contrôlent les insectes phytophages sur une plante cible, sont discutées.

[Traduit par la rédaction]

Introduction

Biological control is simply defined as "the use, by man, of living organisms to control undesirable animals and plants" (Nichols 1989). It is usually applied by introducing new natural enemies of a pest or by manipulating management procedures to favor the natural enemies already present. Biological control can be used for either insect pests or weeds, but it has been almost entirely developed and utilized in agriculture. To date, it has had only limited application for forest insect control and almost never for forest vegetation management. An exception, however, is a multiagency effort, including the USDA Forest Service, the National Park Service, the Hawaii State Division of Forestry and Wildlife, the Hawaii Department of Agriculture, and the University of Hawaii, utilizing biological control to manage a massive invasion of weeds that is devastating the few remaining stands of native Hawaiian forests (Smith 1990; Gardner 1990). The program, initiated in 1982, has targeted 10+ species of weeds and has active programs underway for 5 of them by four entomologists and three plant pathologists. To date, the program has found and released six new natural enemies (five insects and one plant pathogen) and is actively managing three more agents. It is also conducting research on at least 10 new potential biological control agents (Markin et al. 1991; Gardner et al. 1993). The program is one of the larger weed biological control programs in the United States today and at present is the only active biological control program for forest weeds in the world.

As an entomologist and a plant pathologist, we are deeply involved in this program, with responsibilities ranging from exploring foreign countries to find new natural enemies to conducting research on existing natural enemies in Hawaii, to find ways to increase their effectiveness. Based on our experience in the program, and our familiarity with biological control (Markin et al. 1992), we have tried to review the present status of biological control of weeds for forest vegetation management and its possible use in the future.

In agriculture, the majority of insect pests and weeds are of foreign origin; that is, they had been accidentally (or, in

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some cases, deliberately) moved by man from their original home to a new area, such as to another continent or group of islands like Hawaii. In their original home, the insects or plants were part of a coevolved ecosystem where their numbers were held in check by physical or climatic factors and, most importantly, by a complex of natural enemies, both insects and diseases. On being moved to a new area, these organisms escaped from their natural enemies, and if they found the climate and physical conditions satisfactory, they could increase uncontrolled.

To early man, the sudden appearance of a new insect pest or weed could most easily be explained as a chance of misfortune or a curse from the gods. However, as the natural sciences developed during the past century, particularly the fields of taxonomy, evolution, and ecology, the foreign origin of most pests and their lack of natural enemies was gradually recognized. This led to the logical conclusion that one could return to the home of the pest, find its natural enemies, and establish them in the new area to control the organism. By the latter part of the last century, this theory for a new method of control had been proposed, discussed, and a few attempts to move natural enemies had been made. Most, however, were unsuccessful.

In the United States, things changed in the 1860s, when a new pest, a large sucking insect covered with a soft, white waxy excretion that gave it the common name of cottony cushion scale (*Icerya purchasi* Maskell), rapidly spread through the citrus orchards of California. With no effective natural enemies, the cottony cushion scale rapidly built up populations that at first drastically reduced fruit production and eventually began to kill the trees. By 1887, the citrus industry in California was faced with total annihilation and the chief of the Federal Division of Entomology, C.V. Riley, proposed sending an entomologist to Australia to search for the pest's natural enemies and import them into California. His proposal was delayed, since it was viewed as just an excuse for a junket. Opponents also argued that it was a waste of money and that the cottony cushion scale should be controlled by chemical means, which in those days meant the spraying of kerosene emulsions or soaps, or fumigation with hydrogen cyanide. However, by August 1888, funding for the program had been obtained (by rather devious means) and an entomologist, Albert Koebela, left for Australia to begin the search. Between November 1888 and January 1889, Koebela sent 125 small, nondescript ladybird beetles (*Rodolia cardinalis* (Muls.)) to California for release on an infested citrus tree in Los Angeles. In 3 months the beetles, commonly referred to as vedalia beetles, had devoured all the scale on the citrus trees and spread to other trees in the orchard. By 6 months they had devoured all the scale in the orchard and had rapidly moved, either on their own or with man's help, throughout the citrus growing areas of California, and shipment of citrus fruit had tripled. The cost of the entire project was $1500; the small vedalia beetles were hailed as a miracle, and the science of biological control was born (DeBach 1964).

With the success of the vedalia beetle, many other attempts were made over the next 10 years to control other insect pests, but most ended in failure because of the difficulty in transporting natural enemies due to the slow transportation and poor refrigeration. However, other successes slowly followed, and in 1902 the first deliberate attempt to control a weed was made with the release of several plant-feeding insects in Hawaii to control the spiny, poisonous, woody shrub *Lantana camara* L.

While the control of the cottony cushion scale had been a quick, cheap, and spectacular success, the control of lantana was to become a long, difficult program that eventually required over 50 years, and many trips back to South America by different entomologists. Eventually, over 25 different insects were released, 15 of which became established and formed a complex that reduced or eliminated the weed as a pest over 95% of its range in Hawaii (Davis et al. 1992). The difficulty in controlling lantana set a trend in thinking that biological control of weeds was too difficult to be attempted except in extreme cases. This trend has continued today and is evident in a recent review of major biological control programs that showed 225 attempts on insect pests, but only 25 on weeds (Clausen 1978).

The reason for this discrepancy becomes obvious when the science of biological control is reviewed. Biological control of an insect pest can often be done with only one or a very few introduced agents. The effects are usually readily apparent within a few years, and usually no thought is given as to whether the agents being introduced will attack nontarget species of insects. Since many people view any insects in the environment as pests or potential pests, nondiscriminate attack by the introduced parasite or predator is often felt to be a desirable characteristic. For example, the parasitic wasp (*Coccygomimus disparis* (Vierechi)) introduced in 1972 to North America for control of the gypsy moth (*Lymantria dispar* (L.)) was released even though it was known to be nonspecific. A recent survey indicates it now attacks 30 other species of native caterpillars in 14 families (Schaefer et al. 1989).

By contrast, biological control of weeds is more complex and generally more difficult to undertake (Markin 1989; Markin and Yoshioka 1992). A program usually requires a complex of several different agents, each attacking a different part of the plant, and the results are usually not evident for years. Any proposal to control a plant is usually opposed by groups that have found some beneficial use for that particular weed (e.g., grazing, wildlife habitat, nectar source for bees, etc.). Also, and most importantly, the possibility of the introduced agent attacking useful agricultural plants, particularly if they are closely related to the target weed, requires extensive safety testing to prove that the agents are specific only to the target weed.

The difficulty in controlling lantana might have been a permanent setback to the use of biological control for weeds, had it not been for a spectacularly successful program against a weed, this time in Australia. By the 1920s the introduced prickly pear cactus (*Opuntia* spp.) had spread over 24×10^6 ha of rangeland in Australia, usually rendering it totally unfit for grazing. In 1925, a small moth that tunnels into the cactus pads, *Cactoblastis cactorum* (Berg.), was released. By 1930, with some help from other introduced insects, *Cactoblastis* was destroying cactus over a large area, and by 1940 it was credited with having solved the problem and saving the grazing industry (Wilson 1960; DeBach 1964). Despite the spectacular successes of the vedalia beetle and *Cactoblastis*, most accomplishments in weed control over the first 50 years were more in line with those of lantana: slow and difficult with many setbacks. However, by 1940 biological control was a recognized pest management tool with a documented and proven history of successes. Then a setback occurred. The development of modern chemical insecticides and herbicides in the 1940s gave farmers a quick, direct, and reliable method of containing pests, at least temporarily, and biological control of insects and most weeds declined markedly. Biological control was not to recover for 30 to 40 years until our present era of environmental awareness. Fortunately, the low value of rangelands and the relatively high cost of treating them repeatedly with herbicides made biological control of their weeds economically attractive. This resulted in several successful programs against weeds in the United States (Clausen 1978), including Klamath weed (*Hypericum perforatum* L.) in the 1950s, puncture vine (*Tribulus terrestris* L.) in the 1960s, several aquatic weeds in the 1970s, and recently, tansy ragwort (*Senecio jacobaea* L.) (Brown 1989). Biological control of weeds has not been restricted to North America; on a worldwide basis by 1985 it had been attempted against 86 species of weeds, with acceptable to complete control obtained in one-third to one-half the attempts (Julien 1987).

Biological control of weeds in timber production

Previously, we noted that biological control is an old and proven method of pest control, but one that has primarily been utilized in agriculture. In comparison, only a limited effort has been made to use it for forest insect control in North America. However, enough attempts have been successful to show that biological control can be used in our native forest environment (Kelleher and Hulme 1984). While efforts at biological control of forest insects may seem limited, at least this approach has been considered by forest pest managers. In comparison, biological control has almost been totally ignored as a potential tool for vegetation management. In North America, the use of classical biological control in forest vegetation management is almost nonexistent for the obvious reason that our primary goal is establishment or release of desirable tree species from competition, and almost none of the plants that are normally targeted for vegetation management are introduced. There are, however, at least two exceptions that should readily lend themselves to biological control.

Kudzu

In the southeastern United States, the introduced vine kudzu (*Pueraria lobata* (Willd.) Ohwi) is by far the most serious problem in forest regeneration and management (Miller and Edwards 1983). Consideration is being given to using classical biological control for its management. Surveys of kudzu in its homeland in China and Manchuria indicate that it is attacked by a large complex of natural enemies (Pemberton 1989). However, besides the normal problems of finding quarantine facilities where research can be conducted, experienced scientists to do the work, and funding, not everyone in the southeast views kudzu as a problem. Kudzu has several beneficial uses, including as a ground cover for erosion control (the reason it was originally established), grazing, and as a potential agricultural crop for the starch in its roots. Local support by the forestry community and other land management agencies is very high for a biological control program, but interest at an administrative level is presently delaying a program.

Gorse

The spiny European shrub gorse (*Ulex europaeus* L.) is distributed along the West Coast from Point Reyes, California, north to Canada, with its major infestation along the southern Oregon coast between the towns of Bandon and Brooking (Anonymous 1974). As is typical of many weeds that interfere with forest regeneration, gorse seeds lie dormant for a long period in the soil but readily germinate following disturbances by logging or wildfire, then readily outgrow and smother desirable native tree seedlings. Its spiny nature also interferes with access for management and when established as an understory, gorse's high flammability greatly increases fire danger.

So far, one insect, a small weevil, the larvae of which destroy the gorse seeds and would therefore slow further spread of this weed, has been introduced and is successfully established throughout the range of gorse. Gorse is also a problem in Hawaii and New Zealand; the two have a joint biological control program for this weed (Markin and Yoshioka 1989). The program has found and tested 10 potential biological control agents, of which four have been released in Hawaii (Markin et al. 1991). All releases, however, have been made within the last 3 years, so it is too soon to determine if the program will be successful.

Weed management on forest grazing lands

In the western United States, use of forest lands for grazing is probably the second most common source of economic return, after logging. Since many introduced weeds are poisonous or otherwise undesirable for forage, and are capable of replacing desirable forage plants, their invasion on this land is undesirable and their control often is necessary. Since many of these are introduced weeds, they were also ideal candidates for classical biological control. Several rangeland weeds such as Klamath weed (Clausen 1978) and tansy ragwort (Brown 1989) have been successfully eliminated on much forest lands as an incidental benefit of classical biological control programs aimed at these weeds in adjacent pastures and rangelands. Present forest grazing lands also stand to benefit from a major effort to control star thistle (*Centaurea solstitialis* L.), knapweeds (*Centaurea* spp.), and leafy spurge (*Euphorbia pseudovirgata* (sensu Ebke & McCarty) (*Euphorbia esula* L.) by Canadian, USDA Agriculture Research Service, and state entomologists (Kelleher and Hulme 1984; Nowierski 1985). These weed control programs are being actively supported by different regions of the USDA Forest Service. Several insects have already been established on each of the three weeds, and others are under evaluation or ready to be released. The prospects, therefore, are good that in the next 10–20 years successful control will be obtained, at least on the more open forest grazing lands.

Unfortunately, experience has shown that there is no guarantee that even if the rangeland weed programs are successful, the introduced agents will be effective against the same weeds in the shade of a forest canopy or at higher elevations. For example, in Hawaii the weed *Clidemia hirta* L. was a major problem both in rangelands and in forests up to 1950. The introduction of a very small insect, a thrips, successfully controlled the weed in open areas, but was ineffective in forests where clidemia was an understory species (Wester and Wood 1977). Similarly, Hawaii's effort to control cactus (*Opuntia megacantha* L.) was spectacularly successful. On rangeland, plants were eradicated from sea level to 2000 ft (610 m) elevation. Unfortunately, the insects could not survive at the higher elevations of the cactus range, around

3000 ft (914 m), where even now, 40 years later, a small, but healthy population of cactus still remains (Davis et al. 1992).

Protection of native forest ecosystems

In North America, the role of forest vegetation management in silviculture has been almost totally limited to the control of native plant species that compete with desirable economic trees. The control of these undesirable plants is usually not feasible using classical biological control (see above) since they are native plants. However, there is now a rapid trend towards "new forestry" (DeBell and Curtis 1991; Franklin et al. 1986; Franklin 1989), which is rapidly changing the management of forest environments for other values besides timber production and grazing. Two such values are hydrology and wildlife habitat. These uses are drastically impacted by introduced wetland weeds such as purple loosestrife (*Lythrum salicaria* L.), which is now spreading through the tier of northern states and California (Hight 1989), or the aquatic weeds alligatorweed (*Alternanthera philoxeroides* (Martius) Grisebach) and waterhyacinth (*Eichhornia crassipes* Martius (Solms-Laubach)) in southeastern United States (Center et al. 1989).

Other forest uses such as recreation and wildlife habitats are also rapidly increasing in importance and usually require maintaining undisturbed native forests and other natural ecosystems. However, the use that has recently gained the most publicity is the value of undisturbed native forests as habitat for threatened and endangered plants and animals. To meet these new uses, the management of native forests and other natural ecosystems, a whole new generation of forest managers is evolving, with a new discipline referred to as resource management (Stone et al. 1992), or conservation biology (Stone and Stone 1989). As expected, the National Park Service has been the lead agency in natural ecosystems protection and has selected classical biological control as one of its preferred weed vegetation management tools (Gardner 1990; Gardner et al. 1993; Smith 1990).

As public awareness of the value of natural forests and their complex of native animals and plants increases, the pressure to manage forests for these new values will spread from parks and wildlife refuges to all federal and state lands and even private lands when endangered species are involved. The forest vegetation manager of the near future will need to understand and evaluate a whole new complex of weed problems and will more and more frequently find that biological control is an alternative vegetation management tool that will need to be considered (Markin and Yoshioka 1992).

Nonclassical methods of biological control

As mentioned earlier, biological control is not limited to its classical form; it can include the use of any living organism to control another undesirable animal or plant. Several forms of nonclassical biological control may provide usable tools for vegetation management.

Supplemental introduction against native weeds

Since the majority of forest weeds in western North America are native, this situation offers the option of introducing new alien agents that could supplement the native plant's existing complex of natural enemies to increase the impact on the plant. That native plants in North America can be attacked and killed by introduced foreign agents is a well-known but painful fact, as evidenced by the massive destruction of our native chestnuts and elms by pathogens introduced from Asia and Europe. Similarly, foreign insects such as the introduced gypsy moth (*Lymantria dispar* L.) and the larch case bearer (*Coleophora laricella* (Hubner)) readily attacked native trees after being accidentally introduced to North America.

The use of foreign species of insects to control native weeds is an old idea (DeBach 1964; Wilson 1964; Andres 1971), and has been considered for control of poison ivy (*Toxicodendron radicans* (L.) Kuntze) in North America (Habeck 1989) and brackenfern (*Pteridium aquilinum* (L.) Kuhn) in Europe (Lawton 1985). It is now the major objective of a USDA facility in Texas primarily working on rangelands weed control (DeLoach 1978, 1981, 1993). Years of overgrazing or fire suppression have selectively favored unpalatable species such as mesquite (*Prosopis* spp.) (DeLoach 1985), which have greatly expanded in range, dominating huge areas of western and southwestern United States. Mesquite and other native rangeland weeds have been considered, or now are, active targets for biological control by the USDA. Studies have been conducted on relatives of several of our undesirable plants in Argentina to identify some insects that could be introduced to the United States. At least one insect has been tested and released by the USDA against the southwestern rangeland plant snakeweed spp. (*Gutierrezia*) (Cordo 1985; DeLoach 1992).

These programs are not without their opposition from many people working on biological control of weeds (Pemberton 1985). The targeted plants are all important, if not critical, components of the local ecosystem, and their elimination or substantial reduction could have far-reaching impacts on wildlife, native arthropods, and the plant community in general. It can also be argued that alternative methods of control are easier and may be more economical. Among them are modifying our rangeland management practices to lessen grazing pressure and increasing the use of range fires. As would be expected, use of supplemental introductions against native species is opposed by environmental groups and even other federal agencies such as the National Park Service. The programs on rangeland weeds, however, are likely to continue, since environmental interest in these areas is low, at least compared with the interest in other native ecosystems, and because much of the affected land is privately owned.

The use of supplemental introductions against native plants that interfere with reforestation in western North America could possibly work. However, the introduced agents would not remain in the areas that we wish to manage, but would eventually spread throughout the entire range of the target weed, including environmentally sensitive areas such as parks, wilderness areas, protected watersheds, etc. Much of this land is under federal management and consequently under the close watch of environmental groups. Very strong opposition to programs attempting to control these native plants can be expected. It is the authors' recommendation that supplemental introductions should not be attempted for forest vegetation management.

Mycoherbicide

One nonclassical biological control method that has been used successfully to control native plants that are agricultural weeds is the application of naturally occurring plant pathogens, which are isolated, mass produced, then applied to their original host species in the same manner as a chemical herbicide. Many plant pathogens are highly specific and will attack only one species or a very small group of closely related species. Others are highly virulent, but lack effective dispersal mechanisms or are unsynchronized to their host, i.e., the host has time to complete most of its seasonal cycle of growth before the pathogen population builds up enough to do significant damage.

In agriculture, the use of mycoherbicides is a rapidly expanding new area of vegetation management (Charudattan 1985, 1988; Harley and Forno 1992; Templeton et al. 1989). Not only are mycoherbicides highly specific and highly effective, but they are relatively easy to manufacture since the industrial processes for culturing, processing, and registering microbials are all in place. Further, the final product can be packaged and handled like conventional herbicides and can usually be applied with conventional application equipment. Finally, the product can be registered and sold, which can provide a return on the investment of finding, testing, and registering the pathogen. All these factors have made it relatively easy to obtain the financial support for research in this area of biological control.

As usual, this method of biological control is the most advanced in agriculture with its large markets, where to date at least five pathogens have been registered and presently are, or soon will be, commercially available (Templeton and Heiny 1990):

Trade name	Target weed	Crop
Collego™	Northern joint vetch	Rice
DeVine®	Strangler vine	Citrus
Casst®	Sickle pod	Soy bean
Biomal™	Round leaf mallow	Garden and field
Velgo™	Velvet leaf	Corn and soy beans

About 20 more are being tested or are actively under development (Charudattan 1985).

Since the pathogens are naturally occurring organisms already present in the same ecosystems in which they will be applied, Mortensen (1986) concludes that they will be quicker and cheaper to develop than chemical herbicides. Charudattan (1988) estimates that development and registration should cost \$1.5 million to \$2 million for a mycoherbicide as opposed to \$10 million to \$30 million for a conventional herbicide. This might even be less for mycoherbicides aimed at the forest market, since they would not be used on food crops.

The high specificity of some mycoherbicides is a disadvantage since this restricts the size of the market for which they can be sold. The first mycoherbicides being developed, therefore, are aimed at weeds of major agricultural crops, e.g., corn, soybeans, rice, and cotton. However, low registration costs could make management of minor weeds, including targets for forest vegetation management, economically attractive.

To meet the need of the agricultural market, most research on mycoherbicides has been aimed at herbaceous annuals in row crops. Little work has been done on testing and developing of mycoherbicides for woody shrubs or trees, an important target of vegetation management in forest regeneration. However, enough work has been done to indicate that control of woody plants is probably possible (Wilson 1969). It has been demonstrated that naturally occurring pathogens can be used as silvicides for control of wild persimmon (*Diospyros virginiana* L.) (Templeton et al. 1979), oaks (*Quercus* spp.) (French and Schroeder 1969), and wild black cherry (*Prunus serotina* Ehrh.) (Scheepens and Hoogerbrugge 1989). Of more direct relevance, the Canadians have a mycoherbicide program underway in British Columbia aimed at control of a number of targeted forest weeds, including salal (*Gaultheria shallon* Pursh) and alder (*Alnus* spp.) (Dorworth 1989). The potential for using pathogens is illustrated by a review the Canadians conducted on pathogens attacking their 20 most important forest weeds (Singh 1989). On average, each weed had 11.8 foliar diseases, 1.7 root diseases or wilt, 2.8 cankers or galls, and 2.7 stem rots, offering a large complex from which a suitable mycoherbicide could be found.

For forest vegetation management, the use of mycoherbicides appears to be the most feasible method of biological control available. The techniques, already developed and in place in agriculture, should readily be transferable to forestry. With the restrictions and opposition we are facing in the use of chemical herbicides, they should provide a more environmentally acceptable alternative. Also, though there are no reliable figures on the area of managed forest sprayed yearly in the United States for site preparation or seedling release, it would probably provide a large enough market to justify the development of several different mycoherbicides.

With concentrated effort and some luck in finding suitable pathogens, the first agents might be available for use in the field in as little as 5 years, if the track record for agricultural mycoherbicides is any guideline. There would probably be some objection to the mycoherbicides approach by environmental groups or individuals, but the use of an agent already present in the ecosystem and specific to the target plant should minimize opposition, at least when compared with the opposition that almost all other types of vegetation management is likely to produce.

Augmentation

The mass production and release of a natural enemy of a weed is not restricted to plant pathogens. In agriculture, it has been demonstrated that the attack on a pest insect can be augmented by collecting or rearing large numbers of its parasite or predators and releasing them in a small area at a critical time in the biology of the target pest.

On a limited basis this method has also been applied to weeds. Silverleaf nightshade (*Solanum elaeagnifolium* Cav.) is a troublesome perennial weed of southwest rangeland. It was experimentally controlled by mass rearing a foliar-attacking nematode, *Nothanguina phyllobia* Thorne, and applying them by inoculating the soil of pasture dominated by nightshade (Orr 1981). In Mississippi, a weed in cotton fields, purple nutsedge (*Cyperus rotundus* L.), is attacked by the moth *Bactra verutana* (Zeller). However, so few moths overwinter that in spring the nutsedge can conduct its initial surge of growth before the moth population can build up to damaging numbers. It has been shown that by mass rearing and releasing large numbers of the moth early in spring just as the nutsedge is beginning its vegetative growth, the plant can be sufficiently suppressed to allow the cotton to grow enough to eventually shade it out (Frick 1978, 1982; Frick and Chandler 1978). The Australians utilized a similar spring release program for a cochineal mealy bug (*Dactylopios* sp.) for control of prickly pear cactus (*Opuntia aurantiaca* Lindl.) (Andres 1982; Wilson 1960).

In Hawaii, a study is underway on the relationship of the introduced moth *Croesia zimmermani* Clark and its target weed, the introduced blackberry *Rubus argutus* Link. We have found that the moth population drops to very low numbers in winter as its food source, blackberry leaves, is shed. In spring the rapid growth of the blackberry plants greatly exceeds the reproductive capability of the insects and allows the plants approximately 4 or more months of freedom from attack before the insect population builds up to damaging numbers. We have considered a mass rearing program to breed large numbers of *C. zimmermani* during the winter and have them ready for release on the blackberry plants as they start vegetative growth in spring. The approach would not work to control blackberry over the entire state, but only in special ecological areas, parks, and small natural areas where we are concentrating on protecting the native ecosystems. On the mainland, similar research into the relationship of the native weeds and the insect complex attacking them may indicate other areas where inundative release of mass-reared insects may be a useful tool in suppressing or even killing the plants we wish to control in small areas, such as a managed plantation.

New associations

One final example of how research into the relationship of the target weed – insect complex may improve one of our programs is increasing the effectiveness of a plant pathogen. In Hawaii, plant pathogens have been used three times to control weeds. In our search for and testing of potential plant pathogens, we have found that many are very virulent but have poor dispersal capabilities or cannot penetrate the plant's outer defenses, the bark, or the cuticle of the leaves. We also know that some plant pathogens, such as the fungus *Ceratocystis ulmi*, the casual agent of Dutch elm disease that devastated the American elm (*Ulmus americana* L.), utilize an associated insect both to find and be carried to the elm tree and to penetrate its bark to infect the living wood. Accordingly, in our search for new biological control agents in foreign countries, we usually attempt to pair a plant pathologist with an entomologist so that such relationships can be identified in the field. This suggests the possibility of creating a new insect–pathogen association to fit our own need. Many woody plants that we wish to control already have associated bark beetles. This raises the possibility of employing a pathogen that is highly virulent to the plant, but not normally associated with the beetles. If such a pathogen were found, we could mass produce the insect, infest it with the new plant pathogen, and then use the beetle as a selected dispersal and application mechanism. Only extensive research will tell us if such an artificial combination could be created, but this is an example of the ways research on the plant–insect–pathogen combination may lead to new techniques for forest vegetation management.

Environmental manipulation

All native plant species are already being attacked by a complex of plant-feeding insects. However, these insects, particularly caterpillars and beetles, are themselves being attacked by a complex of parasites and predators. This interrelationship produces a balance in which the plant does not expand unchecked but neither do its enemies become so abundant that the plant is exterminated. If we could thoroughly understand this interrelated complex, it is possible that by slightly manipulating certain key elements, we could favor the population of phytophagous insects to the point that their feeding would suppress or stress the target plant enough to meet our management needs. While this theory has never been used as a method of forest vegetation management, it has been considered (Berryman 1991; Berryman et al. 1987).

The history of biological control reveals numerous examples of how environmental manipulation (usually accidental) can affect biological control agents (Goeden and Louda 1976). Recently the Australians reported a resurgence of cactus, which for 50 years had been successfully controlled by the introduced moth *Cactoblastis cactorum*. They found that it was caused by the attack on the moth's eggs by a newly introduced ant (Robertson 1985). Since most forest environments have a very rich ant complex, we can expect that these are major predators suppressing our phytophagous insects (Pavan 1981). Selective ant control might allow these insects to increase substantially. Ant control is a well-developed science (Vander Meer et al. 1990), usually depending on highly specific baits containing very tiny amounts of insecticides. This may offer a possible tool for releasing desirable forest insect populations from ant attack. Birds are also a common predator of forest insects. Studies have been conducted on manipulating their population to release the natural insect population of greenleaf manzanita (*Arctostaphylos patula* Greene) in California (Valenti 1991).

Chemical suppression of parasites

A different approach might be to release populations of desired insects by using insecticides to control the parasites that naturally attack them. The spectacularly successful control of the cottony cushion scale in California was described at the beginning of this paper; however, after almost 60 years of total control, major outbreaks began to appear in the 1940s and 1950s. Eventually these outbreaks were traced to the use of the new chemical insecticides such as DDT (DeBach 1964). Low-dosage treatments or even the drift from adjacent treated orchards was found to eliminate the introduced parasites and predators of the cottony cushion scale, but not harm the scale itself. It is now well documented that different types of insects have greatly differing degrees of susceptibility to many pesticides (Croft 1990). Actively flying parasites are usually more susceptible to a fine aerosol spray of a short-lived pesticide than is their host, such as caterpillars, hidden in tunnels or in silken shelters that filter out the droplets.

In Hawaii we have a persistent problem in using caterpillars as biological control agents for weeds. Many parasites that suppress caterpillars have been accidentally or deliberately introduced and often have a broad host range. We are considering various methods of controlling these introduced parasites. One method, is the use of aerosol sprays to destroy the parasite complex just before our biological control agent reaches the stage where they are susceptible to attack. Another is the use of pheromone traps to reduce the population of parasites during the critical time. Many insects, including the parasites that we are interested in, find their mates by following an odor, called a pheromone, released by the female (Mayer and McLaughlin 1990). The science of identifying and synthesizing pheromones is well advanced, and these materials are now widely used as baits to survey insect populations. They have also been used to control some moths by trapping the males to prevent their breeding with the females.

It might be possible to identify and synthesize the pheromone for a common pupal parasite that is attacking one of our agents and use it to bait traps to destroy the males. A similar program to destroy the male parasites in forest regeneration sites to prevent mating and attack on the desired phytophagous insect might have application on the mainland.

Summary

In the United States, biological control is a science slightly over 100 years old, but one that has been primarily restricted to the control of insect pests or agricultural weeds and, to a limited extent, weeds of range and pasture lands. Only a few efforts have been attempted to use biological control for forest insect pests, and almost no effort has been made to use it for forest vegetation management, where the goal is enhancement and growth of desirable tree species. For forest weeds, classical biological control (the finding, importing, and releasing of the natural enemies of an introduced weed) has been attempted against gorse in the northwest and is being considered against kudzu in the south. In general, since few of our other forest weeds are of foreign origin, classical biological control will probably be of limited use in the foreseeable future. Supplemental introductions where the weed is a native species, and where the natural enemy is found on a related plant in a foreign country and introduced to the United States to supplement the existing complex of natural enemies, are being tried on rangeland. However, attempts to do this in forest environments face the likelihood that the released agent will eventually move from the target area to places where the plant is desirable as a native component of ecosystems. Such an approach in forests is likely to encounter strong environmental opposition and is not recommended. Other methods of biological control include inundative releases in which an insect is artificially reared and released in a limited area or at a specific time to overwhelm the weed, and environmental manipulation where management procedures are used to favor a particular phytophagous insect or pathogen. Both methods have been tried on a limited scale in agriculture, but more extensive research and testing is needing before any of them are applicable to forestry.

The most promising method of biological control that might have immediate use in vegetation management in forestry is the use of mycoherbicides. In agriculture, mycoherbicide use is already well advanced: five pathogens have been found, tested, and registered and up to 20 more are under development. Since the methods for testing are well established and registration procedures are already in place, the technology for forestry use is available. The disadvantage is that many mycoherbicides are very specific and usually attack only one or a very few species of weeds. Since most areas we are attempting to reforest have several undesirable plants, several agents might have to be used or more general pathogens selected and developed. Also, the cost of testing and registering a mycoherbicide may not be profitable because of the small market many of our weeds might offer. However, as the use of conventional herbicides becomes more restricted, their cost goes up, and fewer new ones appear on the market, mycoherbicides represent the most promising and immediate alternative for vegetation management. In the foreseeable future, as we experience a shift in forest management away from timber production to true multiple use, the problem of invasion and degradation of native forest by foreign weeds will become increasingly important. For control of these types of weeds, classical biological control will continue to offer a viable, economical, and permanent method of vegetation management.

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