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EVALUATING BIOCONTROL OF WEEDS PROJECTS

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ABSTRACT

The purpose of evaluating biocontrol of weeds projects is to obtain monetary and scientific feed-back. The first objective relates to the reduction of losses from the weed and requires a pre- and a post-biocontrol assessment. The relationship between the density of a weed and crop yields is curved so the use of average weed densities tends to grossly over estimate losses and hence benefits. If the weed has not reached its distributional limits, an important part of the benefits may have to be obtained by extrapolation. The second objective requires data on the population dynamics of the weed and the agent. Frequently, it requires a combination of stresses to control a weed population, so an agent increasing the stress load is contributing to biocontrol. Seed production and biomass are more sensitive to stress than is the density of the weed but physiological measurements such as water potential may be even more sensitive.

INTRODUCTION

The vitality of biocontrol of weeds requires two types of evaluation before a project is completed. To maintain financial support it is necessary to show that biocontrol is an economical method of solving certain types of weed problems and to improve the effectiveness of biocontrol in the future, it is necessary to have scientific feed-back. Essentially, the first type of evaluation is concerned with what has been achieved and the second with why the result, either success or failure, has been achieved.

ECONOMIC EVALUATION

It was once sufficient to determine the achievements of biocontrol in terms of damage inflicted on the weed: percentage seed destruction, percentage weed reduction, etc. It is now necessary or at least highly desirable to determine monetary benefit. This adds considerably to the work. Also, it does not necessarily follow that damage to the weed is of any monetary benefit, so it is harder to claim success.

Regardless of how the achievements are measured, it is necessary to know the pre-biocontrol situation. All too often biocontrol is started with little or no knowledge of the losses from the target weed and unfortunately this deficiency extends to all areas of weed control. For example, Menz and Auld (1977) pointed out that although legislation in Australia requires the control of galvanized burr, *Bassia birchii*, the losses are too small to make control economic and in some cases the plant is even beneficial. Similarly, in western Canada the conspicuousness rather than the importance of toadflax, *Linaria vulagis*, (Darwent *et al.* 1975) seems to have determined policy regarding this weed. One of the best documented object lessons of starting a biocontrol project without the necessary preliminary study is the insect pest *Loxostege frustalis* in South Africa. According to Annecke and Moran (1977) this project was the most expensive and prolonged in the country and failed completely to solve the problem. Finally, it was found that the pest could be easily and cheaply controlled through pasture management. I hope that all biocontrol of weeds projects now include as an initial step an investigation of the biology of the weed, the

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losses from it and the relative costs of alternative control methods.

The losses from a weed species can be determined from a regression analysis of crop yields *vs.* weed density. These losses vary with site, moisture and other factors. For example, Wells (quoted by Cullen 1978) found 100/m^2 skeleton weed (*Chondrilla juncea*) reduced wheat yields by 80 per cent in dry sites and 50 per cent in moist sites. Such differences can be averaged by random sampling or determined separately by site class. From the regression and a knowledge of weed density before and after biocontrol, it is possible to calculate benefits. However, it must be realized that the losses per weed decrease with its density. Many annual weeds fit the equation $Y = a - b\sqrt{X}$ where Y = crop yield and X = weed density (Dew 1972) while for skeleton weed Cullen (1978) found a logrithmic relationship. This weed-crop yield relationship means that the use of average weed density will greatly over-estimate losses for a weed that occurs in patches. For example, Buchan (1974) using average wild oat densities calculated annual losses for Western Canada at $912 million. Dew (1978) using averages for crop districts instead of the region as a whole calculated the losses as $280 million of which $92.4 million were from Saskatchewan. Thomas (pers. comm.) using the area in five density classes of wild oats lowered the estimates for Saskatchewan to $89.5 million. Biocontrol agents are likely to change the degree of clumping in the distribution of a weed so the use of density classes is especially important.

The labour and cost of a ground survey to determine the effectiveness of biocontrol is high. Cullen (1978) eliminated the post-biocontrol survey by following the decline of skeleton weed with *Puccinia chondrillina* on a few sites over a number of years and then extrapolated. This is the normal approach, but aerial photography offers a relatively cheap and rapid method of surveying dominant weed species over a large area. Armstrong (1979) reported good success with mapping leafy spurge in Montana. I would like to see a study on the cost-effectiveness of aerial survey of several weeds targeted for biocontrol in a range of habitats.

At least part of the yield benefits from the biocontrol of a weed will be lost as other weeds increase to occupy the habitat. Thus, I am confident that the $25.96 million/year benefit from the biocontrol of skeleton weed (Cullen 1978) in Australia will be gradually eroded by the increase of other weeds although the rate at which this occurs will partly depend on the farmer. A farmer who sows uncleaned seed or who over-grazes his pasture is unlikely to benefit from biocontrol for more than a year or two. The replacement of weed species also occurs in chemical control. For example, the chemical control of mustard, *Sinapsis arvensis*, in wheat in Saskatchewan increases cow cockle, *Saponaria vaccaria* (Alex 1970, Hunter 1977), and requires the application of other herbicides. The problem of losses from most replacement species can be side-stepped in biocontrol by making the evaluation shortly after control is achieved, as done by Cullen (1978) and future benefits can be amortized. It is not correct to suggest that all benefits 'will accrue each year in the future' as stated by DeBach (1964) for the biocontrol of St. John's wort in California.

Many introduced weeds will not have reached the full extent of their range when biocontrol is achieved. For example, diffuse and spotted knapweed, *Centaurea diffusa* and *C. maculosa*, in western Canada appear likely to spread from the 30 000 ha presently infested to 10 million ha of uncultivated grasslands (Harris and Cranston 1978). The extrapolated losses are about $58 million/year and the cost of control around $75 million/year. These projected benefits (about 3000 times present losses) certainly justify the cost of biocontrol although the present losses are barely sufficient. Thus, although projections are always open to attack, they may form a major part of the benefits and thus are an essential part of evaluation.

Marsden *et al.* (1980) in their analysis of the returns on Australia agricultural research pointed out that most economic evaluations have concentrated on the successes and ignored the cost of the failures. The attractiveness of biocontrol for future investment depends on the benefit:cost ratio of all projects, both successes and failures. There is a high failure rate in biocontrol of weeds. For example, in Canada only 60 per cent of the agents introduced have become established and only 10 per cent have had enough impact on the weed to produce economic benefits. Thus, there is considerable room for scientific feed-back to improve the success rate and hence the benefit: cost radio.

SCIENTIFIC EVALUATION

One difficulty with scientific studies on the agent-weed system is that there are an almost infinite number of interesting studies that can be done. The impressive studies done by Dodd (1940) on prickly pear and by Clark (1953) on St. John's wort are not models that we can follow in Canada for the 17 species of weeds on which we have released biocontrol agents. We just do not have the man-power available. Thus, I suggest that as far as scientitic feed-back is concerned, the evaluation can be restricted to determination of the reasons for the results achieved. The result may be the failure of the agent to become established, the failure of the agent to control the weed or the successful bio-control of the weed. Each result will require a different type of study and if they are done properly, it should be possible to form concepts from them that can be used to improve the success of future biocontrol projects.

Failure of agents to become established

In my experience, most failures to become established are related to a part-icular problem and the mortality at other stages is largely immaterial. Thus, the objective should be to identify the problem as quickly and directly as possible. Some reasons for failures are mentioned. Many researchers have been able to pinpoint the problem without a great deal of peripheral study.

Reading between the lines of Dodd (1940) it appears that the reason that 70 per cent of the Lepidoptera species released on prickly pear failed to become established in Australia was that they were diseased. The rate of establishment failure in Canada using virus free stock of Lepidoptera is approximately 40 per cent or the same as for other insects.

A better knowledge of leafy spurge taxonomy would have prevented the failure of several European insects in Canada. It appears that there are five taxa of the weed (Dunn and Radcliffe-Smith, in press) and the insects were released on the wrong one. Until recently, all leafy spurge in North America was regarded as *Euphorbia esula*.

One of the leafy spurge taxa in North America is a hybrid. I expect it to be particularly difficult to control as two other hybrids, *Lantana camara* and *Opuntia aurantiaca* have been difficult subjects for biocontrol. According to Stirton (1977) *L. camara* is a man-made polyploid complex of taxa that differs in various ways including its susceptibility to insects. Harley *et al.* (1979) found that the effectiveness of *Teleonomia scrupulosa* varied with the flower colour of *L. camara*; this being the most visible indication of basic differences between taxa. Arnold (1977) suggested that the hybrid origin of *O. aurantiaca* has enabled it to escape insects specialized on either of its parents. Thus, it appears that a high failure rate of agents should be expected on hybrid plants unless relatively unspecialized agents, perhaps accepting the whole genus, can be used.

We have had less success establishing insects in Canada that have been screened in the U.S.A. than those we have screened ourselves. The cause seems to be that the U.S. is selecting species adapted to southern climates. Thus, *Coleophora parthenica* failed in Saskatchewan as the summer temperature much of the time is below the threshold needed for development.

Peschken (1977) found that *Altica carduorum* failed in Canada partly from the depredations of a specialized *Altica* predator. Perhaps we should avoid selecting agents in genera native to North America on the grounds that they are almost certain to encounter specialized parasites already present.

Successful agents

The normal procedure followed with a successful agent is to monitor both weed and agent density over a period of years. The inverse correlation between the two populations is important for demonstrating that the agent is responsible. This relates to economic evaluation but is of little value for the selection of successful agents in the future. The need is for a profile of characteristics that have contributed to success. Obviously a successful agent must be able to achieve a high population density on dense stands of the weed. However, a high population can be achieved by a short generation time, by high fecundity or a low mortality so there are likely to be several successful profiles. I have tried to identify some of the characteristics in a rating system for prospective biocontrol agents (Harris 1973) but the criteria need to be confirmed or rejected on the basis of past successes.

Biocontrol involves an interaction between an agent and a weed so part of the success will depend on the qualities of the weed. Many of the weeds successfully controlled in North America are species already under considerable ecological stress from drought, frost or the competition from other vegetation (Harris 1980*c*). The addition of the biocontrol agent merely raises the total stress load on the weed to a critical level. In regions where the agent is not subject to these environmental stresses, the agent has not achieved control. For example, the cinnabar moth, *Tyria jacobaeae*, has controlled tansy ragwort, *Senecio jacobaea*, in well drained pastures on the east coast of Canada where larval defoliation is supplemented by early frost but defoliation in the longer growing season of the west coast did not achieve control (Harris *et al.* 1978). Similarly, the weevil *Rhinocyllus conicus* has controlled the thistle *Carduus nutans* in Saskatchewan where the thistle is growing in competition with grass but not in gravel pits and disturbed sites where there is little other vegetation. Thus, agents are most likely to be successful if they supplement other stresses on the weed. The stresses may differ between regions or may occur at different seasons so that different agents may be required for maximum effectiveness.

Agents established but not achieving control

The traditional approach to the scientific evaluation of the biocontrol of an insect pest is the life table in which the mortality from various causes is itemized for a number of pest generations and then their role in regulation of the pest is determined. This method is appropriate for an agent that fails to increase but is of little value when the agent is fully exploiting its host as does the cinnabar moth in British Columbia (Harris *et al*. 1978). A life table might be used for the weed to determine the effect of a seed feeding insect but is not appropriate for most insects which weaken the plant by removing a portion of the biomass but do not kill it. Death is often the result of an accumulated chain of stresses over a considerable period and cannot be assigned to any one of them.

The modern offspring of the life table is the simulation model. The idea of being able to try various agents or combinations of agents in a model as a means of selecting the most effective is appealing as it avoids the irreversibility of actual liberation. However, I have still to be shown that models can fulfill this role although they are useful for other purposes. For example, a model of the cinnabar-tansy ragwort system in British Columbia showed variations in the weed could be predicted solely on the basis of rainfall (Lakhani and Dempster 1980) so the observed decline cannot be credited to the cinnabar moth. Nevertheless, as the moth does reduce the biomass of the weed, the project should not be regarded as a complete failure.

An energetics budget avoids many of the difficulties associated with the life table as consumption may be by one agent or several. The objective of biocontrol is to raise consumption above the production of the weed. New (1971) tried an energetics study on the spurge hawkmoth, *Hyles euphorbiaea*, and I would like to see the method explored more extensively with a weed such as *Lantana* that required a succession of defoliators for control. The success of biocontrol of this weed in the drier areas of Hawaii (Andres and Goeden 1971) can be explained by the lower production of the weed in dry than in wet sites. The main difficulty I see with this approach is that 100 grams or calories of foliage removed in the spring may be either more or less damaging to the plant than the same amount removed in the summer. Thus, the consumption by different species of insects are not necessarily additive.

The simplest and often most effective approach is a broad look at the life histories of both the weed and the agent. Annecke and Moran (1978) found that the agents released in South Africa for the biocontrol of *Opuntia ficus-indica* were not fully compatible with either the host or the climate. They concluded that success would have been greater if they had relied less on the agents selected for Australia. Probably, the uncritical transfer of agents from one region to another in the world is a major factor limiting the success of biocontrol of weeds.

The introduction of *Dactylopius austrinus* to South Africa resulted in a spectacular collapse of *O. aurantiaca* followed by reinfestation (Moran and Annecke 1979). Biocontrol was then abandoned in favour of a massive mechanical and chemical eradication program. After more than 20 years the cost and lack of eradication forced another look at biocontrol. According to Gunn (1977) the failure of *D. austrinus* was related to its poor natural dispersion from small and scattered plants. He suggested that this could be corrected artificially. There are also possibilities of introducing agents adapted to small plants. Certainly small and scattered plants of *O. polyacantha* in Saskatchewan are extensively attacked by insects. Thus, in both these South Africa examples, the feed-back seems to have been obtained from general life-histories type studies.

Finally, I suggest that biocontrol can be evaluated in terms of stress loading on the weed. I mentioned earlier that many of the successes in North America result from the combination of several stresses on the plant. Thus, biocontrol can be regarded as a matter of increasing the stress load to a critical level at which the plant declines. The need in this approach is for a means of measuring plant stress—a stressometer. I think that there are both biological and physiological indicators that can be used for this purpose.

A light stress is reflected by a reduced seed production, a moderate stress by reduced biomass and a severe stress by reduced plant density. For example, Myers (1980) reported that defoliation of wild rose by the tent caterpillar, *Malacosoma californicum pluviale* resulted in a ten fold reduction in the number of hips formed. The cinnabar larvae in British Columbia consumed much of the tansy ragwort stem as well as the foliage and caused a reduction of both seeds and plant biomass. In Nova Scotia in places where the effects of cinnabar defoliation were supplemented by early frost, the density of the weed was reduced. Thus, gradations of stress are reflected by the weed in biological terms and a common mistake seems to be the expectation that the individual agent will inflict enough stress to reduce the weed density.

I suggest that an agent should be regarded as a success provided it results in a measurable increase in the stress load on the weed. For example, in British Columbia, the seed-head flies, *Urophora affinis* and *U. quadrifasciata*, have reduced seed production by diffuse knapweed, *C. diffusa*, from around 40 000 seeds/m^2 to around 1500 seeds/m^2 without affecting the density of the weed at the release sites (Harris 1980*a,b*) although Berube (1980) suggested that they may reduce knapweed at the dry margin of its range. As far as I am concerned, the flies are a major step towards control of the weed and the final increases in the stress load to achieve control may be obtained by introducing additional agents, by pasture management, or in other ways.

A physiological indicator that might be useful in many situations is the xylem water tension which can be measured with a pressure chamber precisely and rapidly in the field (Slavik 1974). An indication of its sensitivity is that small amounts of mistletoe, *Phorandendron bolleanum*, increased the water tension in trees (Ferrel 1974). The water tension would be used to select agents that resulted in the greatest increase in the drought stress to which most plants in the temperate zone are subject. In a dry habitat the most serious consequences of defoliation is that root growth ceases. Thus, if you want a closely cut lawn in a dry region, you must water regularly or it will burn. The alternative is to mow high so the grass develops a deep root system and is better able to keep itself supplied. Huffaker (1953) found that the effect of winter and spring defoliation of St. John's wort, simulating defoliation by *Chrysolina quadrigemina* was to decrease the amount of root with the result that the plants were killed by the summer drought of California. I think it possible that defoliation during the summer drought itself might have been detrimental for control of the weed by reducing transpiration losses and hence reducing the drought stress. Insects attacking the stems and roots of a plant have a more immediate and direct effect on plant water balance so their greatest effect may be from attack at a different time of year than defoliators. Measurement of water tension seems to be an easy way of measuring the degree to which various agents can supplement the effects of a natural drought stress.

Water tension might also be used to explain some field results. The gorse weevil, *Apion ulicis*, makes small feeding punctures in the leaves and shoots of gorse that have little effect on the survival of its host except in parts of California where feeding coincides with a severe summer drought. The result then is the death of branches and even whole plants (Hawkes 1965).

CONCLUSIONS

1. An economic assessment should be made of all biocontrol successes. This requires a knowledge of the pre- and post-biocontrol costs and losses associated with the weed. The determination of pre-biocontrol losses has the added benefit that obviously economically unsound projects can be rejected before a large investment has been made in biocontrol.
2. The economic benefits from weeds that are controlled before they have reached their limits of spread should include the benefits from preventing further spread of the weed.
3. Future benefits if calculated should be amortized.
4. A biological assessment involving the collection of data on the population dynamics of the agent and when relevant, of the weed, should be made in all projects.
5. Reasons for the lack of establishment of an agent should be determined as this is of direct benefit to the future establishment of agents.
6. Agents that have become established but do not control the weed are of particular interest for determination of future strategy against the weed and several approaches for their evaluation were suggested. If they have increased the stress load on the weed, they are steps towards biocontrol that can be supplemented by the addition of other agents or by other means.
7. Computer simulation models of biocontrol systems can be helpful for showing the contribution made by an agent in the control of the weed but I am not aware of any examples in which they have been helpful in determining future strategy against the weed.

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