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Proceedings of the Workshop on Biological Control of Pests in Canada

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Proceedings of the Workshop on

Biological Control of Pests in Canada

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Calgary, Alberta

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Edited by
A.S. McClay
Alberta Environmental Centre
Vegreville, Alberta

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ORGANIZING COMMITTEE:

A.S. McClay, Alberta Environmental Centre (Chairman)
M.P. Sharma, Alberta Environmental Centre
W. Yarish, Alberta Agriculture
D. Cole, Alberta Agriculture

PREFACE

The Workshop on Biological Control of Pests in Canada was held at the Carriage House Inn, Calgary, on October 11–12, 1990. In our initial plans, we envisaged an attendance of about 50 people. In fact, the workshop was attended by over 180 participants from across Canada as well as a few from the United States and United Kingdom. Participants came from a wide range of institutions and backgrounds, including researchers from federal and provincial government institutions and universities, extension and regulatory staff from all levels of government, industry personnel, private consultants and producers. This enthusiastic response clearly indicates the timeliness of the Workshop: there is a widespread interest in biological control in Canada, and a wish to know more about its potential.

The workshop was designed to increase awareness and understanding of the potential for biological pest control in Canada, to provide an opportunity for communication among researchers, producers, administrators and others involved in biological control, and to provide a forum for discussion of issues affecting progress in biological control. It consisted of four sessions. In the first, entitled "State of the Art", eleven speakers were asked to summarize the current state of various fields of biological pest control in Canada, and to point out opportunities and problems for further progress.

The second session consisted of reports on individual programs or issues, in the form of poster presentations. Twenty-two posters were displayed, covering a wide range of topics from regulatory issues to the cold-hardiness of insect parasitoids. Abstracts of the posters are included in these Proceedings.

The third session was entitled "Current Issues". The three speakers in this session addressed the regulatory position of biological control in Canada, recommendations for implementing biological control programs, and global trends in biological control.

In the fourth and final session, entitled "The Way Ahead", participants broke up into four discussion groups. These groups were asked to consider respectively: research needs; coordination and funding; regulation; and implementation of biological control programs. The moderators of these groups then reported their conclusions to the reassembled workshop participants. Summaries of these reports are included in these Proceedings.

As will be clear, the two days of the Workshop were crowded ones. Even with a full program, some areas could not be covered; for example, we had no papers on biological control in forage crops, fruits or vegetables. The feedback received from participants showed that most found the workshop to be interesting and useful. A glance around the meeting room during the talks usually revealed intense note-taking, suggesting that the speakers were presenting information which was both new and interesting for many of those present. Many commented that they particularly benefited from the opportunities for informal meetings and discussion with other biocontrol workers.

Possibly the most significant development at the Workshop came during the final session. The discussion group on "Coordination and funding" concluded that there was a need for a permanent forum to promote biological control in Canada, which would provide leadership, set priorities, and promote communication among those interested in biological control. This proposal was unanimously endorsed by the workshop participants. A three-person steering committee, consisting of Roberte Makowski (Agriculture Canada, Regina), Bill Turnock (Agriculture Canada, Winnipeg) and myself was elected to develop plans for such an organization, tentatively named the Canadian Forum for Biological Control. These proposals will appear in the next issue of the Agriculture Canada publication *Biocontrol News*, a copy of which will be sent to all those who were registered at the Workshop. The plans will be revised on the basis of comments received on these proposals, and it is hoped that an inaugural meeting of the Forum will be held in 1992.

I would like to thank all those who assisted with the Workshop, in particular: the members of the Organizing Committee; Alberta's Minister of the Environment, Hon. Ralph Klein, for his warm welcome to the participants and his encouraging opening remarks; Dr. Fayyaz Qureshi, Director of the Plant Sciences Division at the Alberta Environmental Centre for his interest and support; all the speakers; the moderators of the sessions and discussion groups; Centre technicians Rob Hughes, Neil McLean, Sharon Kendall and Nancy Cowle for much hard work in the preparation, set-up and running of the workshop; and the staff of the Carriage House Inn for dealing efficiently with a rather larger group than we expected.

These Proceedings have been produced from manuscripts submitted on diskettes by the speakers. One paper is not included as it had not been received by our publication deadline. They have been edited for consistency of style, spelling and format, but are otherwise essentially as submitted. Statements or opinions presented in them reflect the views of their authors, and not necessarily those of Alberta Environment or Alberta Agriculture.

A.S. McClay
January 1991

SESSION 1: STATE OF THE ART

Biological Control in Greenhouses

L.A. Gilkeson
Applied Bio-Nomics Ltd., P.O. Box 2637, Sidney, British Columbia V8L 4C1

ABSTRACT *The use of biological control is well established in the Canadian greenhouse industry. Reasons for this are reviewed, including benefits to growers, forces in the marketplace, and the leading research done in Canada. The current status and details of biological control programs are described, including* Encarsia formosa *to control whiteflies,* Phytoseiulus persimilis *to control spider mites,* Aphidoletes aphidimyza *to control aphids,* Amblyseius cucumeris *and* Orius tristicolor *to control western flower thrips,* Geolaelaps *sp. to control fungus gnats and other predators for minor pests. Recent changes in the greenhouse industry and their impact on the application of biological controls are also discussed and recommendations are given for areas requiring further research and development.*

INTRODUCTION

The Canadian greenhouse industry comprises about 650 ha of vegetable and ornamental crops. Although it is small compared to the greenhouse industry in the Netherlands, with its 9600 ha of greenhouse vegetables, it is economically important because of the high farm gate value of the production. There are about 300 ha of vegetable crops in greenhouses in Canada (Shipp 1988), primarily tomatoes, long English cucumbers, sweet peppers and lettuce. The most common ornamentals grown are roses, chrysanthemums, poinsettias, asters and carnations, although gerberas, alstroemerias, freesias and others are also entering the market. The bedding and nursery plant industry is very large, especially around major cities, and there is a growing number of conservatories and interior plantscapes in offices, malls and public buildings. Greenhouse production in Canada is scattered from coast to coast with vegetable production concentrated in such areas as the lower mainland of British Columbia, the Medicine Hat area of Alberta, the Leamington area of Ontario and the region of St. Hyacinthe in Quebec.

Biological control of pests in greenhouses has been studied since 1926, when the parasitic wasp *Encarsia formosa* Gahan was first introduced to control greenhouse whitefly in English greenhouses. With the advent of DDT and other broad spectrum pesticides in the 1940s, the use of biological control agents virtually ceased. Then growers in the Netherlands began to have problems with pesticide resistant spider mites in the 1950's. In 1962, the discovery of the predatory mite *Phytoseiulus persimilis* Athias-Henriot, which is an excellent predator of spider mites, revived interest in using *Encarsia* to control whiteflies and stimulated research into other biological control species and mass production methods.

In 1990, it was estimated that biological control was applied in over 12,000 ha of greenhouses in the world (of a total world area of 150,000 ha)(van Lenteren 1990). About half of Canadian greenhouses use biological control either solely or for part of the crop season. In western Canada most vegetable greenhouses use biological controls (over 85% in British Columbia, 55% in Alberta); in the rest of Canada tomato growers alone use the majority of biological controls.

Greenhouse growers are increasingly replacing pesticides with biological controls for several reasons, including the fact that they frequently achieve better control of the pests with the natural enemies (van Lenteren 1990). Pesticide resistant flower thrips, aphids, whiteflies and spider mites are common in greenhouses, particularly in ornamentals, and one of the main benefits of biological control is that it offers a way to control strains of pests that have become resistant to pesticides. Yield increases of 20-30% have been reported in cucumbers in England (Hussey and Scopes 1985) and a recent study in commercial greenhouses in Alberta found that growers using chemicals to control western flower thrips in cucumbers had a 30–40% lower yield than growers using biological controls (Steiner 1988). Growers also find that it is easier to maintain harvest schedules when there is no need to observe pesticide withdrawal times and, as the British Columbia vegetable growers have discovered, the export marketability of produce without pesticide residues increases the value of their crop. The growing public demand for regulatory restrictions on agricultural pesticide use is a further incentive to switch to biological control, as is the fact that, in common with chemicals for other agricultural crops in Canada (Stermeroff and Culver 1987) the list of pesticides available to the greenhouse industry is steadily decreasing. Fewer new insecticides are available because chemical companies are unlikely to recover their development costs for pesticides used only by a small industry (van Lenteren and Woets 1988). New crops, such as sweet peppers, have few registered pesticides and there is little prospect that this will change with the difficulty in obtaining minor use registrations.

BIOCONTROL AGENTS IN USE

The following is a brief review of the present spectrum of biological control agents used in Canadian greenhouses, including some species that are promising prospects for future use in commercial greenhouses.

Whiteflies The tiny parasitic wasp *Encarsia formosa* lays its eggs in the greenhouse whitefly [*Trialeurodes vaporariorum* (Westwood)] immatures and as the larvae grow they kill the whitefly. The whitefly scales then turn black as the wasp pupae develop inside, making it easy to monitor the level of parasitism in the whitefly population. Most insectaries remove *Encarsia* pupae from the leaves and glue them to cards that are easy to distribute among the plants. In Canada, *Encarsia* mass production started in 1970 at the Harrow Research Station in Ontario, and by 1973 about 4 million were sold to growers (McClanahan 1980). Since then, supplies of *Encarsia* have grown, both from the two Canadian insectaries and from several European suppliers. During 1990, the British Columbia insectary alone shipped 25 million *Encarsia* to Canadian growers (D. Elliott, pers. comm.). It is estimated that about 75% of Ontario tomato growers use *Encarsia* at least part of the season on their crops; about 85% of British Columbia tomato growers use it as do 30–40% of Quebec growers (Shipp 1989).

Release rates for greenhouse tomatoes and cucumbers have been well established over the last 20 years of use, however, the challenge now is to develop the use of *Encarsia* on ornamentals. More poinsettia growers are using biological control this year than ever before in Canada, many with encouraging results.

No discussion of whitefly control is complete without a description of sweet potato whitefly, *Bemisia tabaci* Gennadius, which is a new pest for the Canadian industry. It is a serious problem in poinsettia production worldwide and in 1990 a few greenhouse tomato growers also had severe problems with this pest. Sweet potato whiteflies are often highly resistant to pesticides, they attack a wide variety of plants, including all of the commonly grown greenhouse vegetables and ornamentals, and they can be vectors for virus diseases. *Encarsia formosa* does parasitize this species and although sweet potato whitefly does not seem to be the its preferred host (Boisclair et al. 1990), some results this year suggest that *Encarsia* may be sufficiently adaptable to control the sweet potato whitefly on tomatoes, if not on poinsettia.

Researchers in several countries are currently studying other biological controls for sweet potato whitefly, such as the parasitoid *Eretmocerus* sp., and a small black lady beetle *Delphastus pusillus* Casey. The latter species feeds on both species of whitefly and is currently being reared experimentally in Canada.

Spider mites The predatory mite *Phytoseiulus persimilis* has been used since 1970 in the Netherlands to control the two-spotted mite, *Tetranychus urticae* Koch, which is a serious pest in greenhouse cucumbers. Spider mites also attack tomatoes and peppers and are particularly severe in hot, dry conditions, such as in greenhouses on the prairies during the summer or under high intensity lights. The predator is exceptionally effective against spider mites because it is so voracious and reproduces twice as fast as the spider mites, enabling it to catch up to a spider mite infestation within a few weeks. The predators are supplied to growers on bean leaves (with some prey), or are removed from leaves and shipped in a bran or vermiculite carrier. Unfortunately, the quality of mites shipped in granular carriers has been generally poor and a substantial number of growers now request predators on leaves, even though it requires more labour to distribute them.

P. persimilis is generally the most reliable of the biological controls available commercially and the easiest for growers to learn to manage. Unfortunately, it is rare for spider mites to be the sole pest in a crop. If pesticides are necessary to control other pests, then it is much more difficult to get a biocontrol program working because the predators will be killed. One way around this problem is to use pesticide resistant *P. persimilis*, an approach that has interested researchers for several years (reviewed by Hoy 1985). Among the many promising species of predatory mites, lines have been isolated or artificially selected for resistance to organophosphorus and carbamate insecticides, sulphur, and synthetic pyrethroids. Most are still in the laboratory stage, but a few lines are being mass-reared and are becoming available from commercial insectaries.

Aphids Controlling aphids has always been a problem in bedding plants and ornamentals, but it was not until commercial growers started growing sweet peppers that biological control of aphids became important in greenhouse vegetable crops. Aphids, particularly green peach aphid, *Myzus persicae* (Sulzer), are a key pest in this crop and a great deal of research in Canada has been devoted toward managing the biological control of aphids in peppers in the last five years. The aphid midge *Aphidoletes aphidimyza* Rondani, which has been available commercially in Canada since 1986, preys on over 60 species of aphids, including all species that occur on greenhouse plants. Female midges lay their eggs among aphid colonies, where the larvae feed on aphids; after 3–5 days they leave the plants to pupate in the soil. In peppers, releases of 1–2 midges per plant (or about 12,000–24,000 per 0.5 ha) weekly as needed have been found most successful for controlling aphids (Gilkeson 1990). Cost is about $4000 per 0.5 ha per year, which is expensive, but is comparable to pesticide costs (depending on the labour for applying chemicals) and tolerable for growers exporting this crop because there are so few alternatives. Results on sweet peppers have been best when the aphid parasitoid *Aphidius matricariae* Haliday is established in the greenhouse, either from artificial introductions or from native populations entering the greenhouse. Although native hyperparasitoids take their toll on *Aphidius* populations during the summer, *Aphidius* is less inclined to diapause under winter greenhouse conditions than the aphid midge and can be an important, or even sole, component of a biological control program from fall through early spring. Studies on using the aphid midge to control aphids in greenhouse roses, chrysanthemums and other crops are currently under way.

During the last 2-3 years in Canada, infestations of the melon aphid, *Aphis gossypii* Glover, started appearing in greenhouse cucumber crops; in 1990 they began to infest peppers as well and have become a very serious problem because of their resistance to pirimicarb. Although both *Aphidoletes* and *Aphidius* attack melon aphid, it is still too early to tell whether they can provide control. The extremely high reproductive rate of this aphid, especially on cucumbers, makes it very difficult to control and it is expected that if they are to succeed at all, release rates must be very high. In England, *Aphidoletes* have been used with success to control melon aphid on chrysanthemums.

Thrips Several species of thrips occur on greenhouse plants, including western flower thrips, *Frankliniella occidentalis* (Pergande), which started spreading through the North American greenhouse industry in the mid-1980's. Western flower thrips have now become a widespread problem in greenhouse in both the U.S. and Canada, especially since pesticide resistant races have become common. They feed and lay eggs in flowers and leaves, causing curled fruit in cucumbers, and severe blossom and leaf damage in ornamentals. Perhaps their most devastating effect is yet to be seen, because they also spread tomato spotted wilt virus, which is looming as a major problem on a wide range of vegetable and ornamental plants.

The predatory mite *Amblyseius cucumeris* (Oudemans) is now used widely in Canada and Europe to control onion thrips and western flower thrips in greenhouse vegetable crops. Although large numbers of predators must be released to control thrips in cucumbers, the mites are relatively cheap to produce so that the cost of using them is about the same per hectare as using pesticides. A drawback to using this predator is that the mites are only capable of attacking immature thrips (the adult thrips are too large), therefore it takes several months for biological control to succeed and occasional migrations of thrips entering from outdoors in the summer can overwhelm the capacity of the predator population to control them. Nevertheless, many growers have had good results using the predator mites, particularly on sweet peppers, and there have been promising research results on ornamentals such as chrysanthemums (Parella, pers. comm.).

A larger predator, the minute pirate bug *Orius tristicolor* (White), which is now being mass-reared and released experimentally in Canada, is proving to be a better control for thrips than the phytoseiid mite because it is a voracious predator of all stages of thrips. The adult bugs are also attracted to cucumber flowers, which is where western flower thrips cause the most crop damage. Pirate bugs also feed on spider mites and seem able to remain present at low pest densities for long periods in the greenhouse, feeding on a variety of small arthropods, pollen and plant juices. In trials in commercial cucumber greenhouses during the last two years, thrips populations were reduced to very low numbers within 5-7 weeks after a single release of one bug per 1-2 plants. An unanswered question with this predator is whether early or late season releases will continue to reproduce or whether they will diapause as some other native species do in greenhouses (e.g. *A. aphidimyza* and *A. cucumeris*).

Fungus gnats Fungus gnats are often present in greenhouses and when they occur in high numbers, the larvae damage the fine root hairs of plants as well as becoming an aesthetic pests in ornamentals. Growers are now paying more attention to fungus gnat control because it has been shown that the larvae can spread *Pythium* root rot in cucumbers and *Fusarium* in tomatoes. The native predatory mite *Geolaelaps* spp. is a promising biological control for fungus gnats that seems to thrive in the top layer of soil or growing media such as sawdust and vermiculite, and does well in moist areas where fungus gnats reproduce. Usually a single release of mites early in the season on seedlings is enough to establish the population throughout the greenhouse. Experimental releases on poinsettias in1989 achieved excellent control of fungus gnats, however, more research must be done on the specificity and species complex of these predator mites before their use can become widespread. Controlling fungus gnats with applications of nematodes or *Bacillus thuringiensis israelensis* is currently being tested in a few commercial situations.

Other pests The main pests in commercial vegetable greenhouses and their biological controls have been described, however, there are several that occur primarily in interior plantscapes or conservatories in Canada. Several species of mealybugs are controlled by the Australian lady beetle *Cryptolaemus montrouzieri* Mulsant, and the mealybug parasite *Leptomastix dactylopii* Howard is sometimes available from US insectaries. A range of natural enemies for soft and hard scale is also available, including the coccinellids *Chilocorus nigritus* (F.) and *Lindorus lophanthae* (Blaisdell) and the parasitoids *Aphytis melinus* DeBach and *Metaphycus helvolus* (Compere). Although not an insectary reared species, the convergent lady beetle, *Hippodamia convergens* (Guérin), is sold by Californian insectaries and can be used to control aphids and mealybugs in greenhouses or conservatories. Lacewings, both *Chrysopa carnea* Stephens and *Chrysoperla rufilabrus* (Burmeister) are also sold for control of soft-bodied pests. *B. thuringiensis* is used by growers to control alfalfa loopers and other lepidopterous pests that occasionally enter greenhouses from outdoors and build up troublesome populations under glass.

THE CHANGING APPLICATION OF BIOLOGICAL CONTROL

As the Canadian greenhouse industry has grown and changed over the years, so has the application of biological controls. For example, at one time all greenhouse vegetables were grown directly in soil beds; now many growers use soilless media, such as rock wool, bags of sawdust or peat, or nutrient film and hydroponics systems. Planting schedules have changed in the industry from seasonal production of tomatoes and cucumbers to nearly year-around production. Some growers now set out plants in December or January and continue with the same crop through the following October or November; others put in two or even three successive crops during the course of the year. The trend towards a long or continuous cropping season has important implications for the use of biological controls because most of the native, temperate zone species now in use enter diapause under winter greenhouse conditions of short days and cooler night temperatures. Growers using lights to extend the daylength or who keep high night temperatures, such as in propagating houses for cucumbers early in the season, may not have problems with maintaining their biological controls, but other growers may need to try different species, use higher release rates or integrate a pesticide for off-season control of pests. Diapause in the aphid midge, *A. aphidimyza* can be prevented by leaving on extremely low intensity light all night (Gilkeson and Hill 1986), whereas in the thrips predatory mite, *A. cucumeris*, increased daylength does not seems as effective as maintaining temperatures above 20°C at night (Gilkeson et al. 1990). Low light levels in the winter also reduce the oviposition of *Encarsia* even though this species does not diapause, and the cooler conditions in winter generally favour development of homopteran pests over their predators and parasitoids.

There is a changing scale of production in the Canadian greenhouse industry, with a shift toward new, state-of-the-art structures covering as much as 2–5 hectares per operation. Apart from the fact that such large operations strain the current supplies of biological controls, we are also beginning to see that the logistics of controlling pests in greenhouses of this magnitude are somewhat different than in the smaller greenhouse operations of 0.5 ha or less that have characterized the Canadian industry in the past. Measures to balance pest and predator populations, such as using yellow sticky traps to reduce adult whitefly populations, that might have been reasonable in a small greenhouse are simply impractical on a large scale. With the larger areas involved there is a greater chance of native pests entering greenhouse vents and building up high populations.

MAKING BIOLOGICAL CONTROL IN GREENHOUSES WORK IN THE FUTURE

There is considerable room for expanding the application of biological controls in greenhouse crops in Canada, both in well-established applications such as tomatoes and cucumbers and in newer applications such as ornamental and bedding plants. A key requisite is training growers, extension workers and advisory personnel how to manage and monitor biological control programs. Contact between researchers, growers and advisory services must be close and immediate to translate the latest information from research trials into practical programs and to provide feedback from growers to researchers and advisors. Local training programs for greenhouse workers on how to recognize, apply, and monitor biological control programs are very useful in ensuring a successful transition from a chemical control program. Biological control suppliers must be able to back up products with information, and ideally with research results under Canadian conditions; this has become a recent problem with European products sold in Canada through local distributors who have little or no experience with using them.

Quality of biological control agents is a recurring problem with several aspects. Growers must be able to count on a certain level of quality, which can be related to a certain level of efficacy or else it become impossible to get consistently successful results. Because the Canadian greenhouse industry is distributed across an enormous geographical area, nearly all biocontrol products are shipped for longer or shorter periods to reach the growers. Shipping delays or handling errors can have an important impact on the quality of the predators received by the growers. Growers themselves can ruin a product by delaying releases or storing them under incorrect conditions. Part of the solution to this problem is in development of shipping containers, such as those with diets included, that allow mites and insects to survive longer handling periods under adverse conditions. Quality of the biocontrol agents coming from the rearing systems is also a problem, which is not unique to the Canadian industry; insectaries worldwide must address quality problems in their rearing cultures, from latent diseases to drifting genetic characteristics. Comparatively little is known about arthropod diseases, particularly those in phytoseiid mites, and this is an area requiring more research.

In summary, over the last 20 years, biological control has become a key pest management strategy for pests in greenhouse crops worldwide. Although biological controls have only been used widely in Canadian greenhouses within the last ten years, it is fair to say that Canada is now a world leader in research on and the application of greenhouse biological control agents. With the increasing availability of biological control agents to growers and the research currently being conducted on new beneficial species, their release rates, management, and application in diverse crops, the future prospect for biological control in Canadian greenhouses is excellent.

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Biological Control of Insect Pests of Field Crops

W.J. Turnock
Agriculture Canada Research Station, 195 Dafoe Road, Winnipeg, Manitoba R3T 2M9

ABSTRACT *Classical biological control of field crop insects has not been attempted often in Canada. The proportion of successes is encouraging but new attempts are being discouraged by a generally defeatist attitude concerning biocontrol in this annual crop environment. Current emphases on reducing use of chemical pesticides, and the looming spectre of resistance to biological insecticides, emphasize the need for inclusion of various types of biological control in pest management systems. Implementation of all control operations should be based on monitoring the pests and their natural enemies. The introduction of exotic biocontrol agents and the enhancement of the effectiveness of all agents should be regarded as means to reduce pest numbers within the management system. Biological insecticides have an important role as alternatives to chemical insecticides when crop protection is needed. Their potential should not be jeopardized by their widespread use in transgenic plants as this would increase the likelihood of genetic resistance in the pests.*

INTRODUCTION

Biological control attempts in field and row crops have been limited in Canada as in other countries. Neither classical biological control (introductions) nor the use of biological insecticides (including inundation releases with *Trichogramma* spp.) have had a large impact on pest control in field crops. I will discuss the two approaches separately before concluding with remarks on the potential use of biological control in Canadian field crops.

CLASSICAL BIOLOGICAL CONTROL

Attempts to establish exotic natural enemies of field crop pests in Canada have been limited in number. Against field crop pests, some cases of successful suppression of pest populations are recorded.

1. The ichneumonid *Collyria calcitratrix* (Gravenhorst) against the European wheat stem sawfly, *Cephus pygmeus* L., in eastern Canada in the 1930's (Turnbull and Chant 1961).
2. The eulophid *Tetrastichus julis* (Walker) against the cereal leaf beetle, *Oulema melanopus* (L.), in Ontario in the 1970's (Harcourt et al. 1984).
3. The braconid *Ascogaster quadridentata* Wesmael against the pea moth, *Laspeyresia nigricana* (Stephens), in British Columbia in the 1940's (McLeod 1962).
4. The introduction of a virus originally isolated from *Euxoa ochrogaster* (Guenée) was shown to be feasible to control *E. messoria* (Harris) in Ontario tobacco fields but this project was discontinued (Cheng 1984).
5. A strain of *Aleochara bilineata* (Gyllenhal), a staphylinid parasitoid/predator of the cabbage root maggot, *Delia radicum* (L.), was selected for resistance to cyclodiene-type insecticides to restore this species to its former position as a natural control agent in Prince Edward Island in the 1960's (Read 1971).

Unsuccessful introductions are similarly few in number:

1. Parasitoids of grasshoppers in the 1940's (McLeod 1962).
2. An egg parasitoid of the pea weevil, *Bruchus pisorum* L., in British Columbia in the 1940's (McLeod 1962).

3. Parasitoids of the carrot rust fly, *Psila rosae* (F.), in eastern Canada in the 1940's and 1950's (McLeod 1962).
4. Although a few of the parasitoids released in the 1950's in eastern Canada against the European corn borer, *Ostrinia nubilalis* (Hübner), became established, the program was not regarded as successful (McLeod 1962).
5. Several species of parasitoids against the wheat stem sawfly, *Cephus cinctus* Norton, in western Canada in the 1930's (Turnbull and Chant 1961).
6. The braconid *Townesilitus bicolor* (Wesmael) against flea beetles, *Phyllotreta cruciferae* (Goeze) and *P. striolata* (F.), in Manitoba, 1978-83 (Wylie 1988). Small numbers of parasites for release, difficulties in propagation of hosts and parasitoid, and lack of funds for extended work overseas terminated this project.
7. The tachinid *Eutheria consobrina* (Meigen) against the bertha armyworm, *Mamestra configurata* Walker, in Manitoba, 1986-87 (Turnock 1984, unpublished data). *E. consobrina* has not been recovered and is now impossible to collect in western Europe. Lack of funds to extend the search to the USSR and China have led to the end of this project.

Although the proportion of successes could be considered encouraging, Canadian workers have accepted the generally defeatist attitude that developed concerning biological control in field and row crops. This opinion has been encouraged by the instability of this environment, where the crop persists only a short period of time. The harvest is commonly followed by destruction of crop residues and tillage of the soil, and crop rotation imposes a regular movement on pest and natural enemies. In these circumstances, the establishment of effective host-natural enemy relationships has been deemed more difficult than in more stable environments. In addition, biocontrol practitioners appear to have shared, at least in part, the attitudes common in crop protection circles since the advent of DDT. Control techniques focus on protecting crops that are already infested and success is measured by the rapid death of a high percentage of the pests following application of the technique. Reduction of pest populations in an integrated management system has only recently begun to affect these attitudes. This negative attitude to biological control persists, despite several substantial successes in Canada and elsewhere.

Additional evidence that natural control agents are not always deterred by the impermanence of annual crops is given by the case of the banded sunflower moth (*Phalonia hospes* Walsingham) and the sunflower moth (*Homeosoma electellum* Hulst). Outbreaks of these species occurred for a few years after the introduction of commercial sunflower growing in southern Manitoba, but subsequently the species have fluctuated at low levels. The parasitoids of these species are credited with this control, after a lag during which the parasitoid adapted to the commercial fields (Turnock 1977).

INUNDATION AND BIOLOGICAL INSECTICIDES

In recent years, practical attention in biological control has focused on inundative methods, and particularly on the potential for biological insecticides. Inundation with parasitoids or predators and the use of biological insecticides are similar in concept and in their potential for commercialization. The emphasis in developing these products is on production techniques, reliability, patentability, registrability and cost-effectiveness as well as their speed of action, spectrum and selectivity of target species and interactions with weather and other bioclimatic factors. These potential impediments to commercialization led Jutsum (1988) to conclude that the use of biological insecticides will increase but they will not replace chemicals in the foreseeable future.

Trichogramma spp. dominate inundative programs around the world. In Canada, *Trichogramma* has not been used in field or row crops although large areas of maize, sugar cane, cabbages and other field crops are treated in Eurasia. Cost-effectiveness and quality control in production facilities are problems even in countries with long traditions of use (China and USSR). In general, *Trichogramma* spp. are not being used against pests of un-irrigated crops of semi-arid regions. If a production facility is established in Canada, much research would be needed to identify effective strains for specific pests and to develop methods of delivering the parasitoids to the field. The egg-parasitoid fauna of Canada is poorly known and well-adapted species might be present. However, the cost, logistics of delivery and the sensitivity of *Trichogramma* spp. to weather will likely limit their use to situations where conditions are favourable and the use of other insecticides is not feasible.

The bacterial insecticide *Bacillus thuringiensis* Berliner (*B.t.*) has been successfully commercialized and emphasis is now on the identification and development of strains effective against insect pests not affected by the original products. In field crops, a *B.t.* for Coleoptera has promise for use against Colorado potato beetle, in areas where resistance to insecticides is a problem and also in insecticide rotations to retard the development of resistance. The international emphasis on finding *B.t.* strains for specific pest situations (by testing natural strains and genetic engineering) will lead to new products that will extend their use in pest management. For example, strains effective against the bertha armyworm and other noctuids are being developed at the Winnipeg Research Station.

Fungal insecticides, mainly *Beauveria* spp., are being used in some countries (e.g. China) but the problems of cost-effectiveness, registrability etc. listed above will have to be solved before these insecticides are commercialized in Canada.

OPPORTUNITIES AND NEEDS FOR BIOCONTROL

Recent publications on biological control (Wood and May 1988, Baker and Dunn 1990) provide overviews of the current situation and opportunities for the future. These can be summarized in relation to the Canadian situation as follows:

Biological insecticides (including the results of genetic engineering) Commercial developments will concentrate on the major markets and benefits to Canada will tend to be auxiliary, as they are for chemical insecticides. The mechanisms for testing and registering insecticides (including the minor use program) also apply to the bioinsecticides. A search for new strains that are present in Canadian environments could initiate the commercialization of products more adapted to our climate. Biotechnology is a currently popular concept in biological control and the potential and problems in engineering improved biocontrol agents are presented in Baker and Dunn (1990). Transgenic plants which produce *B.t.* endotoxins are being produced. The ecologically naïve approach of implanting such endotoxin genes in plants invites rapid development of pest resistance to the toxins. This would deprive us of our most successful bioinsecticide. More sophisticated approaches are needed to integrate transgenic techniques into biocontrol strategies. For example, Strong (1990) suggests that plants designed to produce *B.t.* delta endotoxins should have their expression restricted to the plant part attacked by the pest and that the expression be limited in time to the most critical period of attack. Such a strategy could provide maximum yield protection while minimizing the exposure of the pest to the endotoxin, and avoid imposing selection for resistance on all phytophages.

At present, the poor cost-effectiveness of *Trichogramma* spp. makes them unlikely to be used except in special cases where environmental values override the cost. If an efficient production centre becomes available, a search for local strains and testing of available strains for efficacy against the target species will be high priorities.

Classical Biological Control The creation of a more effective guild of natural enemies through the introduction of new species is ecologically and economically appealing. The "complete successes" of past programs have stabilized pest populations at a level below the economic threshold. Although this objective remains desirable, current emphases on the necessity to reduce the economic and environmental burden of chemical insecticides increase the importance of "partial successes". It has become obvious in recent years that we are unlikely to solve a pest problem with a single approach. Classical biological control and the enhancement of natural enemies are obvious approaches to pest population reduction and thus to lower crop losses and less insecticide use.

There is a growing demand for the use of biological control practices in food production. Consumer demand for reduced pesticide residues, and company reluctance to develop new, specific pesticides open the door to greater use of biological, cultural and physical control methods. This provides an opportunity for entomologists to obtain funding for programs based on monitoring and greater reliance upon natural enemies. To make biological control work we need "money, time, luck and a little bit of scientific insight" (Waage and Greathead 1988). They further suggest that our progress will be speeded by the application of the growing body of ecological theory that is being applied to biological control.

The phases necessary in the development of a classical biological control program are well known. Current Canadian practices and constraints to the development of programs were reviewed at the Biological Control Workshop, Winnipeg, October

1986 (Research Branch 1987). Unfortunately no action has been taken on the recommendations arising from this workshop. I have updated the description of the phases, current practices and problems from the report of the workshop (see Appendix).

CONCLUSION

Major points in developing pest management systems that encourage biological control and minimize the use of broad-spectrum insecticides are:
1. Control programs of any kind should be based on a monitoring (sampling) program for the pests and their key natural enemies. To safely rely on natural enemies, monitoring plays an even more critical role than in strictly chemical based programs. The historical lack of monitoring programs as the basis of past pest control strategies is an impediment to integration of biological and natural control now. Potato growers in British Columbia previously used broad spectrum pesticides to control lepidopterous pests and flea beetles. This led to aphid outbreaks that were not linked to the use of broad spectrum materials until monitoring programs were developed that demonstrated the connection. *B.t.* and selective chemicals are now used when needed in conjunction with pirimicarb for selective aphid control when natural enemies are shown by monitoring to be insufficient. Insecticide use has plummeted as a result of monitoring and the greater reliance upon indigenous enemies of aphids.
2. Biocontrol, particularly the introduction of exotic agents and the enhancement of the effectiveness of all such agents, should be considered as part of a pest management package. An agent that aids in reducing pest populations and thus leads to a reduction in the costs of crop protection should be valued, and not condemned because it fails to provide complete control.
3. Biological insecticides, including genetically-engineered forms, will be developed commercially. Their penetration of the chemical insecticide market will depend on their success in solving the problems that currently limit their use (Jutsum 1988). In pest management, their use will pose the same problems of overuse, misuse and the development of resistance that have affected chemical insecticides.
4. Breeding for resistance, including genetic engineering and transgenic plants, is not considered by some to be part of biological control (see discussion by Cate 1990). Nevertheless, attention by plant breeders to characteristics that reduce insect pest populations or damage to the crop will help to reduce the necessity for crop protection responses. The simplistic use of transgenic plants should be avoided as it could induce resistance in the pest to available or potential biological insecticides. Transgenic plants, like other crops with resistance to insect attack, should be used within the context of a pest management system.

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APPENDIX: Development of A Classical Biocontrol Program

PHASE I. Selection of Target Pests

Requirements

1. Economic evaluation of crop losses attributable to the pest and the economic, environmental and social costs associated with current control practices.
2. Evaluation of existing biotic control agents in relation to pest population dynamics and control practices.

Current Practices

1. Target species are selected on the basis of local initiatives and are approved mainly on the decision of local management. There is no organization or encouragement to evaluate the potential for biocontrol of various pests nor to set national or regional priorities for selecting and approving programs and allotting resources.
2. Economic analyses and evaluation of natural enemies are also usually incomplete. Evaluation of proposed target pests is usually incomplete due to the lack of a data base, the availability of special expertise, and difficulties in committing resources to long-term programs.

Problems

1. *Commitment.* Biological control is said to be a priority for research in Agriculture Canada but these priorities are not evident in program leadership or the allocation of resources.
2. *Resources.* Information on the natural enemies and the population dynamics of Canadian insect pests is fragmentary. Expertise or resources are often lacking for these long-term studies.
3. *Regional programs.* Grass-roots cooperation among scientists in different stations is regarded as desirable but funds to nourish such cooperation are minimal and no mechanism for regional program development is operational.

PHASE II Selection of Exotic Agents

Requirements

1. Determine the availability in foreign areas of control agents of either the pest species or species that are related taxonomically or ecologically to the pest.
2. Determine, from studies in Canada or abroad, the suitability of candidate species: a) will they attack the target species or strain found in Canada and develop on it; b) do they respond to the physical environment (temperature, moisture, photoperiod etc.) in a manner that will ensure survival in Canada and synchronization with susceptible stages of the pest; c) do they have the population characteristics needed for control of target pest (functional and numerical responses to host density, member of guild that is missing or ineffective on target species; d) have they adequate host specificity; e) will they have access to the environmental features necessary for establishment and success in Canada, such as food sources, alternate hosts, overwintering and mating sites.

Current Practices

1. Most of the inventory research and the detailed studies of potential biocontrol agents are conducted through contracts with the CIBC. There is a well-developed protocol for screening and selecting phytophages for the biological control of weeds. In contrast, there is no similar protocol accepted for enemies of insect pests; this depends on local expertise and the availability of foreign information.

Problems

1. Lack of a protocol for evaluating proposed importations and for providing a basis for allocating priorities among proposals.
2. Insufficient interaction between local biocontrol personnel and CIBC.
3. Lack of resources to finance the evaluation of the natural enemies of foreign insects of interest to Canada and to develop the mechanisms needed to stimulate such studies in other countries, particularly the USSR and China. The species in which we are interested are often minor- or non-pests that have not been studied. Under appropriate international agreements, the funding of graduate students in their own countries to do theses on species of interest to Canada might be a useful combination of educational aid and self-interest.

PHASE III. Collection, Importation and Release

Requirements

1. Good working agreements with source countries leading to contracts or other arrangements to supply needed agents.
2. Good quarantine and screening facilities.
3. Good facilities for pre-release handling and propagation if necessary.

Current Practices

1. Most foreign collections are made through contracts with the CIBC. Arrangements are generally satisfactory except for the problems noted above for the Soviet Union. New initiatives are needed to develop cooperation with China.
2. Quarantine facilities are available at Ottawa, Montreal, Guelph and Regina. Additional quarantine facilities may be needed at other locations if major biological control programs are started.
3. Propagation and release are handled by local program personnel. Expertise may be lacking at some locations but, in general, large-scale propagation is not desirable for inoculative releases and scientists who have developed a program to this stage can probably mobilize adequate facilities for limited propagation.

Problems

1. Inadequate support for foreign collections.

PHASE IV. Evaluation and Documentation

Requirements

1. Determination of the establishment and spread of the introduced species.
2. Evaluation and documentation of its impact on the target pest.

Current practices

1. Post-release studies and their documentation are the responsibility of local program personnel.

Problems

1. There is inadequate commitment to the long-term intensive studies of the target pest and its enemies that are necessary to demonstrate the impact of the imported agent on the pest populations and to modify pest management practices to enhance their impact.

Biological Control of Forest Pests by Insect Parasitoids

V.G. Nealis and D.R. Wallace
Forestry Canada, Ontario Region, PO Box 490, Sault Ste Marie, Ontario P6A 5M7

ABSTRACT *Forest insect pest management has several distinctive features which make biological control particularly attractive. Biological control by inoculative releases of imported parasitoids against introduced forest pests has been very successful in Canadian forestry. Current emphasis is on inoculative releases of foreign parasitoids against native insect pests and the establishment of natural enemies which are important at endemic pest densities. In the future, new initiatives in Asian forests will expand the potential source areas for new biological control agents. Inundative releases of parasitoids have been underutilized in forestry. Recent advances in mass-production technology, release strategies and demonstration of the feasibility of inundative releases in the forest environment will lead to further development of this method of biological control. Future successes in biological control will remain dependent on a strong commitment to population biology research and on the development of predictive models for design of biological control strategies and their incorporation into integrated pest management programs.*

INTRODUCTION

The term biological control is often used to include both direct and indirect methods of reducing pest densities through the action of biotic agents. In this presentation we will restrict our discussion to direct methods: the active release of arthropod natural enemies, insect parasitoids in particular, against forest insect pests.

There are two principal strategies for releasing natural enemies: inoculation and inundation. The inoculation (or introduction) of a new natural enemy into a system is biological control in its classical sense. The primary objective of an inoculative release is to establish a viable, founder colony of the natural enemy. Once established, the natural enemy will persist in the area of inoculation and hopefully spread to inflict an annual level of mortality on the pest population over a wide area. The inundative release strategy involves the propagation of a large number of one particular natural enemy species and releasing them into a pest population. In contrast to inoculative releases, where the objectives are sustained and extensive control, inundative releases emphasize current year reduction of the pest population in the immediate area of the release (Nordlund 1984).

Before summarizing the current programs and the future opportunities for biological control of forest pests in Canada, it is worth considering the forestry perspective for the practice of biological control.

THE FORESTRY PERSPECTIVE

The distinctive nature of the forestry context in insect pest management makes biological control a particularly attractive strategy (Balch 1960).

Trees take many years to mature. Compared to an agricultural crop, the forest stand has a very long rotation time and a low annual growth rate. The per hectare value of a forest stand is consequently lower, making conventional pest control less cost-effective in many forest pest situations.

Forest pest outbreaks in mature Canadian forests are typically extensive. During the 1980s, for example, the eastern spruce budworm, *Choristoneura fumiferana* (Clemens), caused 6 to 36 million ha of moderate-to-severe defoliation annually, while in western Canada the mountain pine beetle, *Dendroctonus ponderosae* Hopkins, has killed more than 200 million mature trees in the past ten years (Moody 1990). Persistent outbreaks such as these may require repeated annual treatments. But in any one year, only a fraction of the infested area can be treated by conventional means. For example, the maximum amount of area defoliated by the spruce budworm which was treated by chemical or microbial insecticides in any one year throughout the 1980's was only 16% (Moody 1990). This two-tiered management approach where high-value areas are protected and lower-value stands ignored is only a partial solution. Some measure of pest control is still required in the extensive, low-value stands to prevent highly mobile forest pests from overwhelming the intensively managed areas. Of course, the lowest possible cost will be needed for pest management in these low-value stands. The sustaining nature of biological control is economically attractive in these forest situations (Hulme 1988).

The intermittent nature of extensive forest pest outbreaks creates an economic disincentive for conventional pest control by discouraging investment in the development and registration of new insecticides and by creating inconsistent and often remote markets for applicators. This is becoming an increasingly critical issue in forest pest control making the initiation of new biological control programs imperative (Carrow 1990).

Another reason why biological control is particularly well-suited to forest pest management is that trees are relatively resilient to insect damage. Certainly there will be measurable growth loss from moderate defoliation, and insects which attack growing shoots can seriously affect the form and subsequent market value of a tree by a single attack. But in general, it is not necessary to reduce forest pest infestations as drastically as is demanded in many agricultural situations. Consequently, control need not be perfect and some time-lag between treatment and result is not of as much concern to forest pest managers as it might be to their colleagues in agriculture (Balch 1960).

The intensively-managed new forest is vulnerable to new and specific insect pests for which biological control may be the most realistic, and perhaps the only, control strategy. Tip weevils (*Pissodes* spp.), budmoths (*Zeiraphera* spp.) and various cone and seed insects are important complexes of plantation pests for which control is difficult due to the cryptic habits of the damaging stages. Stage-specific biological control agents would be an effective approach in these situations. The relatively high silvicultural investment and small areas involved in these plantations might make inundative approaches economically feasible.

Forests are complex natural ecosystems. There is a high diversity of insect herbivores in forest ecosystems (Strong et al. 1984). This high diversity is an advantage for the exploration phase of a biological control program because one can expect a correspondingly rich complex of natural enemies from which to choose candidates for inoculation. For this same reason, it has been argued, it may be more difficult to successfully establish new natural enemies (Pschorn-Walcher 1977). This latter concern would be most significant in situations where little was known about the indigenous natural enemy complex. In Canada, the tradition of long-term population studies of forest pests means that the characteristic features of the existing natural enemy fauna are, at least qualitatively, well-known. This permits identification of biological control candidates which complement rather than compete with the existing guild of indigenous natural enemies. Further, unlike agriculture, where the system is frequently disturbed by pesticides, cultivation and harvesting, biological control releases can be made in forest areas where interference is minimal. Analysis of biological control programs on a worldwide basis indicates that the rate of successful establishment of biological control agents is higher in relatively stable environments such as forests than in frequently disturbed crop environments (Hall and Ehler 1979).

Our most destructive forest pests in Canada are native insects with long ecological associations with the forest. For the most part, they already have a rich and varied fauna of natural enemies attacking them. Biological control initiatives are much less likely to interfere with these existing relationships than will the application of insecticides. With biological control, there is more opportunity to work in harmony with the natural complex.

An increasingly important aspect of the forest as a natural ecosystem is public perception. Despite the relatively small volume of insecticides used, spray programs in forestry have a disproportionately high public profile and attract public criticism (Carrow 1990). The reality is that whatever the scientific and pest management merits of biological control, its use is more publicly acceptable. With most forestry operations in Canada on public land with government agents responsible for control, public opinion cannot be underestimated as a factor in pest management decisions.

INOCULATION OF NEW NATURAL ENEMIES

Historically, the inoculation of new natural enemies has been most frequently used against introduced pests on the premise that these introduced pests have escaped the natural controls of their native ranges. The biological control program aims to rectify this by importing the missing natural enemies. In forest pest management in Canada, the method is a proven success with demonstrable reductions in pest numbers following the introduction of parasitoids against several introduced pests including European spruce sawfly, *Gilpinia hercyniae* (Hartig), European pine sawfly, *Neodiprion sertifer* (Geoffroy), European pine shoot moth, *Rhyacionia buoliana* (Schiffermüller), mountain-ash sawfly, *Pristiphora geniculata* (Hartig), larch sawfly, *Pristiphora erichsonii* (Hartig), and winter moth, *Operophtera brumata* (L.) (Kelleher and Hulme 1984). In fact, five of the seven biological control programs in Canada which Beirne (1975) considered successes involved forest insect pests.

The gypsy moth, *Lymantria dispar* (L.), is currently Canada's most notorious introduced forest pest. Canada has benefited from the natural redistribution of biological control agents introduced into the United States throughout this century and the successful introduction into Ontario of two egg parasitoids, *Ooencyrtus kuvanae* (Howard), and *Anastatus disparis* Ruschka (Griffiths and Quednau 1984). As has been the American experience, however, gypsy moth continues to extend its range and to cause severe defoliation despite the action of these natural enemies. This is perhaps not surprising as the gypsy moth commonly causes severe defoliation in its home range (Mills 1990).

That different densities of forest pest populations have distinctive natural enemy faunas was proposed by Pschorn-Walcher (1977) and has been reviewed recently by Mills (1990). A comparison of parasitism from various gradations of gypsy moth outbreaks in Europe show that outbreak and non-outbreak populations support parasitoid faunas which are different in both species composition and rank order of abundance (Fuester et al. 1983; Mills 1990; Maier 1990). There is evidence that parasitoids which operate effectively at low densities may be important at regulating gypsy moth populations at endemic levels (Elkinton et al. 1989).

In view of this, the strategy for the classical biological control of gypsy moth by Forestry Canada is to focus on the role of natural enemies in maintaining endemic populations of the gypsy moth rather than in reducing outbreak populations. To carry out our study, Forestry Canada collaborates with colleagues of CAB International at the European field station in Switzerland. Artificial outbreaks of gypsy moth are established by placing small laboratory-reared gypsy moth larvae on selected trees in areas where gypsy moth populations are characteristically sparse. These larvae act as traps for parasitoids. They are recollected after a predetermined period of time and the parasitoids reared from them. Over the past 8 years, the program has demonstrated that the distinct guild of parasitoids attacking endemic populations of the gypsy moth is dominated by one parasitoid, *Ceranthia samarensis* (Villeneuve) (Mills 1990). As a result, *C. samarensis* has been the focus of our importation and release program (Mills and Nealis 1991).

The most damaging insects in Canada's forests today are not introduced but native insects. Conventional wisdom holds that inoculations of foreign natural enemies are less effective against native pests. That view has been challenged (Carl 1982). Hokkanen and Pimentel (1984) claim that new parasitoid-host associations may actually be more effective than those based on long associations between a host and its parasitoids, although their interpretation has been criticized (Goeden and Kok 1986; Waage and Greathead 1988). Our view is that there are insufficient theoretical or practical reasons to preclude attempts to introduce foreign natural enemies against native pests. Examples of successful establishment of effective, new host associations can certainly be found. The importance of native forest pests and the decreasing conventional control options in Canada make us reluctant to dismiss the possible success of such an approach.

On the contrary, in forest entomology there may be good scientific reasons for considering new host-parasitoid associations for biological control. In Canada, there is detailed information on the population biology of major native forest pests and their indigenous natural enemies. At the same time, we have good information on biological control candidates in Europe (Mills 1983a,b; 1985). The result is that a degree of preliminary analysis can be carried out to determine the suitability of particular new host-parasitoid associations.

A current case history of an attempt to colonize a foreign parasitoid which attacks a native pest is the recent introduction (1990) of the European parasitoid *Apanteles murinanae* (Capek and Zwölfer) against the eastern spruce budworm. This is an especially interesting case, not only because it represents a new host-parasitoid association, but because the introduced parasitoid has a very similar life history to that of a native parasitoid, *Apanteles fumiferanae* Viereck. It was therefore important to examine potential competition between the introduced and indigenous parasitoids. The study is an example of how existing biological information on native parasitoids can be used to evaluate the probable success and possible outcome of a biological control program before releases are made and to decide whether or not a release should be made at all (Pschorn-Walcher 1977). The study can also be considered a test of the value of introducing species which are ecologically comparable to species which are already present.

The natural host of *A. murinanae* in Europe is *Choristoneura murinana* (Hübner). The restricted range and limited size of populations of this insect in Europe meant that less than 100 individual parasitoids could be shipped to Canada in any one year. Moreover, the timing of the shipment was not optimal for releases the same season. This necessitated the development of a rearing program in Canada. Because of the similarity of *A. murinanae* to the native parasitoid, a mass-rearing technique was first developed using the native parasitoid (Nealis and Fraser 1988). The method was then successfully applied to *A. murinanae*. Having demonstrated the biological compatibility of the European parasitoid for its new host, emphasis turned to a comparison of life-history parameters of the two parasitoids which were considered important in possible competitive interactions (e.g. rate of development and age-specific fecundity). Additional experiments were designed to directly assess the outcome of both species searching for hosts within the same patch.

To summarize the unpublished data, the foreign parasitoid, *A. murinanae*, was found to have a slightly slower rate of development and longer pre-oviposition period than did *A. fumiferanae*. This means that adult *A. murinanae* would be searching for hosts later than *A. fumiferanae*. This is relevant as both species of parasitoid are solitary and first-instar parasitoid larvae quickly cannibalize supernumerary eggs or larvae. Trials in which spruce budworm larvae were exposed first to one species of parasitoid and then the next demonstrated that the first parasitoid to attack was the species which successfully completed parasitism. Thus, comparative life history parameters indicate that the temporal advantage lies with the native species. More importantly, female adult *A. murinanae* are less active searchers and have a lifetime fecundity when attacking spruce budworm of only half that of the native *A. fumiferanae*. Trials in which spruce budworm larvae were exposed to both parasitoid species at the same time showed that the native species consistently produced more offspring than did the introduced species and that the per capita rate of parasitism by the native parasitoid sharing a caged arena with the introduced parasitoid was not less than the rate of parasitism when of the native parasitoid was alone. These studies, therefore, indicated that a release of *A. murinanae* could be expected to add to, rather than subtract from, the overall rate of parasitism of the spruce budworm.

Given these results, the first experimental releases of *A. murinanae* have been made in a semi-isolated woodlot in western Quebec where spruce budworm populations have been increasing for the past three years (J. Régnière, pers. comm.). This site was chosen because of its isolation from continuous softwood stands and because moderate to high densities of spruce budworm are expected for the next several years. To monitor establishment of the introduced parasitoid in the field, a sentinel method, once again first developed and tested on the ecologically similar native species (Nealis 1988), will be used.

The future of new biological control introductions in forestry largely depends on the continuation of strong contacts with the CAB International Institute of Biological Control for European work and with the initiation of new foreign exploration in Asia. There are forested areas in the People's Republic of China which are ecologically similar to the forests of eastern Canada (Burger and Shidong 1988). These Asian forests have a high diversity of forest insect species taxonomically related to important forest pests in Canada (*Lymantria*, *Choristoneura*, *Pissodes* etc.) (Forest Insects of China 1980) but are mostly unexplored with respect to biological control agents. Where comparisons of parasitoid complexes of Asia and the West have been made (e.g. gypsy moth), the Asian natural enemy fauna appears more diverse and complete (Fuester and Ramaseshiah 1989). There have been successful explorations in the Orient by the USDA and a proposal is now before Forestry Canada for a three-year program of field explorations and importation of beneficial forest insects from China.

INUNDATIVE RELEASES OF NATURAL ENEMIES

The inundative release of insect parasitoids is a relatively recent biological control strategy in forestry. Most examples are reported from the USSR (Voronin and Grinberg 1981) and China (Cock 1985). The most significant North American studies are the recent inundative releases of the egg parasitoid *Trichogramma minutum* Riley against the eastern spruce budworm in northern Ontario (Smith et al. 1990b). The objectives of the program were to develop the technology associated with an operational inundative release of a native parasitoid against an outbreak population of a forest pest and to determine the effectiveness of the method in decreasing subsequent larval populations of the pest (Carrow 1990). The program involved detailed strain selection (Smith and Hubbes 1986), development of mass-rearing methods (Laing and Eden 1990), monitoring techniques (Smith et al. 1990c), analysis of results (Smith et al. 1990b) and development of models to examine improvements in release strategies (Smith and You 1990; You and Smith 1990).

The program successfully demonstrated that the significant logistical and technical problems of handling large volumes of biological material could be mostly overcome and a successful inundative release made. The monitoring methods allowed tracking of dispersal rates of the parasitoids from the release sites, demonstrated that a significant reduction in egg mass densities of the pest occurred in the treatment areas and permitted the estimation of optimal release rates under natural conditions (Smith et al. 1990c).

Because inundative releases often involve parasitoid species about which there is considerable biological information and which are very specific in the stage of the host they attack, inundative releases have considerable potential as effective components of integrated pest management programs in forestry. A recent example is an integrated control program against gypsy moth in Virginia (Ticehurst and Finley 1988). The program was implemented to reduce or prevent defoliation in urban areas where the tree values were high and the use of pesticides unacceptable. Components of the program included public information, intensive surveys and monitoring, mechanical removal of gypsy moth eggs and larvae, pheromone trapping, the application of microbial insecticides, and inundative releases of three species of parasitoids. The program was considered a success and illustrates the advantages of using specific, environmentally acceptable biological methods to achieve control.

Further development of inundative release strategies in forest insect pest management is largely dependent on the availability of large numbers of natural enemies and hence on the development of cost-effective mass production technology. For egg parasitoids such as *Trichogramma*, the mass production technology is developing rapidly (see Voegelé et al. 1988).

The Ontario *Trichogramma* project emphasized the need for mass production of natural enemies and has led to a 5-year program (beginning in 1989), sponsored by the Ontario Premier's Council Technology Fund, to develop a mass-rearing facility for *Trichogramma* in Ontario. Under this fund, CIBA-GEIGY will develop a production unit. Basic research on production technology and application strategies will be conducted at the Universities of Toronto and Guelph in conjunction with the Ontario Ministry of Natural Resources.

With these encouraging initiatives, inundative releases in Canada have a definite future. A reliable source of quality natural enemies will not only permit continuing research on the biological aspects of host-parasitoid relationships but will provide the opportunity to initiate releases against a greater variety of forest insect pests. By examining the feasibility of inundative releases against several target pests, there will be an expansion of market opportunities which is crucial to the commercial viability of the technique. Inundative releases will certainly become more attractive once their effectiveness against, for example, cryptic pests in high-value plantations or in environmentally sensitive areas has been demonstrated.

CONCLUSION

The peculiar nature of the forest system makes it an excellent stage for the practice of biological control. Unlike conventional pest control which emphasizes protection of current year foliage, the objective of biological control is long-term protection against severe pest damage, either through reduction in the frequency or in the severity of outbreaks. The history of successes in inoculative releases of natural enemies in forestry is impressive and provides sufficient incentive to continue with foreign explorations for new beneficial insects. At the same time, Forestry Canada operates an extensive national survey and monitoring service (the Forest Insect and Disease Survey) with the capability of detecting and identifying newly introduced forest pests.

The approach to inoculative releases is much broader today than when the primary targets were introduced pests. Now, native forest insect pests are of most concern and we are as interested in the role of parasitism in endemic populations as we are in outbreak pest populations. This has led to the examination of novel tactics such as the introduction of foreign parasitoids against native insects and the use of trap hosts to collect parasitoids attacking low-density pest populations.

As forestry continues to develop the new, highly-managed forest, more sophisticated and integrated approaches to pest management will need to be implemented. Inundative releases with their attributes of specificity and system compatibility will be more and more employed as integral components of modern biological control.

One of the strengths of forest entomology in Canada is the tradition of long-term and extensive population studies and of basic research in entomology. The fruits of these endeavours have served biological control very well in the past. For example, the work on winter moth by Embree (1966) remains one of the exemplars of the scientific approach to biological control. The fact that the information originally gained from this biological control effort can still provide a basis for new scientific interpretation (Roland 1988) emphasizes the heuristic value of fundamental research in biological control.

Continuing basic research on the population ecology of forest pests will be crucial for future development of biological control programs. With demands for more cost-effective pest control, greater emphasis may be placed on modelling to predict the outcome of particular introduction strategies (Waage 1990) and the integration of biological control with existing silvicultural and pest control methods (Barclay 1982, Waage et al. 1985). Predictive models, however, are very demanding of basic biological information (e.g. Gutierrez, Hagen and Ellis 1990) if they are to be successful. No matter whether we call our modern approaches to pest control integrated pest management or decision support systems, the need for specialized information at the organism and population level is as great as ever.

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Microbial Control of Forest Insect Pests

J.C. Cunningham and K. van Frankenhuyzen
Forestry Canada, Forest Pest Management Institute, P.O. Box 490, Sault Ste Marie, Ontario P6A 5M7

ABSTRACT *Environmental concerns about chemical pesticides in forestry have resulted in increased interest in, and use of, microbial control. In Canada, research has been conducted on bacteria, viruses, protozoa, fungi and nematodes for control of forest insect pests. However, only the bacterium* Bacillus thuringiensis *(*B.t.*) is available for large-scale operations. It has been applied mainly on spruce budworm, with 2.8 million hectares treated between 1985 and 1990. Smaller areas were treated for jack pine budworm, gypsy moth and eastern hemlock looper. Use of other microbial agents is insignificant compared to* B.t. *Two viral insecticides are registered in Canada for Douglas-fir tussock moth and one for redheaded pine sawfly. Registration is being sought for baculoviruses for European pine sawfly and gypsy moth. Recombinant DNA technology has made genetic manipulation of microbial control agents possible. Genetically engineered* B.t. *products are already available for some insect pests, and genetically engineered baculoviruses are under development.*

INTRODUCTION

Canada has always been a world leader in the development of biocontrol products and strategies, particularly in the forestry sector. Forestry is Canada's most important natural resource and the forests that support this industry are prey to several major insect pests. Research on microbial control of forest insect pests got a tremendous boost when the European spruce sawfly, *Gilpinia hercyniae* (Hartig), was controlled by a nuclear polyhedrosis virus thought to have been accidentally introduced with parasites imported from Europe in the late 1930's (McGugan and Coppel 1962). This is one of the few examples of classical biological control with a microbial agent; 50 years later this insect is still at an endemic level, held in check by the virus and parasites.

J.J. de Gryse, Chief of the Forest Service Investigations of Canada, was greatly impressed by the decline of the European spruce sawfly and thought that the same formula could be applied to control another major forest pest, the spruce budworm, *Choristoneura fumiferana* (Clemens). As a result of his efforts, the Laboratory of Insect Pathology was established in Sault Ste Marie with Dr. J. McBain Cameron as the officer-in-charge, Dr. G.H. Bergold and Dr. F.T. Bird as virologists, Dr. T.A. Angus and Dr. A.M. Heimpel as bacteriologists and Dr. D.M. MacLeod as mycologist. Early successes included discovery of a highly effective virus for control of European pine sawfly, *Neodiprion sertifer* (Geoffroy), (Bird 1953) and pioneering work on *Bacillus thuringiensis* Berliner (*B.t.*) (Heimpel and Angus 1959; Angus 1964). Dr. Vladamir Smirnoff of the Laurentian Forestry Centre and Dr. Oswald Morris of the Forest Pest Management Institute later played dominant roles in establishing *B.t.* as an operational alternative to synthetic chemical pesticides for control of spruce budworm (Smirnoff and Morris 1982).

In any discussion of microbial control of forest pests in Canada, *B.t.* holds centre stage and other agents are insignificant in comparison. The term microbial agents includes viruses, microsporidia, fungi and nematodes. Three viral insecticides have been registered by the Forest Pest Management Institute and petitions for a further two have been submitted. Small scale ground-spray trials have been conducted in Canada with microsporidia and fungi on forest tent caterpillar and spruce budworm, but further development is not contemplated at present. Entomopathogenic nematodes, which carry pathogenic bacteria, are of particular interest because they are not regulated under the Pest Control Products Act and because nematodes can actively search for insect larvae. Ground spray trials with nematodes have been conducted on spruce budmoth, *Zeiraphera canadensis* Mutuura and Freeman (D. Eidt, pers. comm.). This review will, however, concentrate on *B.t.* and viruses which are operationally available alternatives to chemical insecticides.

The advent of recombinant DNA technology has revolutionized biotechnology and is having a major impact on the development of microbial insecticides. It is now possible to engineer a microorganism to effectively control a particular insect pest in a particular habitat. Several products which are the result of genetic manipulation of *B.t.* are already available and more are being developed. Likewise, there is considerable interest in engineering entomopathogenic viruses, and baculoviruses in particular, with a view to developing more effective, environmentally acceptable viral insecticides.

BACILLUS THURINGIENSIS

Mode of action *Bacillus thuringiensis* is a rod-shaped, Gram positive, crystalliferous, spore-forming bacterium. When cultured under appropriate conditions, it sporulates and forms a crystalline parasporal body containing delta-endotoxins. When sporulation is complete, the bacterial cell lyses and releases spores and crystals into the surrounding medium. When ingested by susceptible insect larvae, the crystal, which is composed of large molecules of protoxin, is solubilized by alkaline gut juices and is broken down by gut proteases releasing smaller potent delta-endotoxins. These activated toxins severely damage gut cells, followed by spore germination and septicemia, which kills the insects (Heimpel and Angus 1959). Two noteworthy points are that *B.t.* has to be ingested to kill larvae and there is no secondary infection from *B.t.* released from dead larvae.

Varieties of *B.t.* There are over 1,000 strains of *B.t.* in a type collection, but only three are important in commercial products. *B.t.* subsp. *kurstaki* is used in most commercial products for control of lepidopterous insect pests. Most major defoliators of trees are in this Order. *B.t.* subsp. *israelensis* is active against Diptera and is used to control blackflies and mosquitoes. It may have potential for controlling dipterous pests of cones, although this has not been tested. *B.t.* subsp. *tenebrionis* is effective against Coleoptera. Again, it has not been used in forestry, but may have some practical applications.

Table 1. *B.t.* products registered in Canada for forestry use.

Registered	Trade Name	Potency (BIU/L)	Supplier
1973	Thuricide 16B*	4.2	Zoecon
1978	Novobac-3*	8.6	Biochem
1980	Dipel 88*	8.4	Abbott
1981	Thuricide 32B*	8.4	Zoecon
	Thuricide 32LV*	8.4	Zoecon
1984	Bactospeine	9.7	Duphar
	Thuricide 48LV	12.7	Zoecon
	Futura*	14.4	Chemagro
	Thuricide 32F*	8.4	Zoecon
	Dipel 132	12.7	Abbott
1985	Envirobac-ES	8.4	Pfizer
1988	Dipel 176	16.9	Abbott
	Futura XLV	14.4	Chemagro
1989	Dipel 48AF	12.7	Abbott
	Dipel 64AF	16.9	Abbott
1990	Foray 48B	12.7	Novo
	Futura XLV-HP	33.0	Chemagro
	Biodart	16.9	ICI

*Discontinued

***B.t.* products** *B.t.* is produced by fermentation technology using an inexpensive protein source such as soy meal. Crystals and spores are harvested and suspended in a liquid, either as an emulsifiable oil formulation or an aqueous flowable formulation. There are currently 18 *B.t.* products registered for forestry use in Canada, although none is produced in Canada (Table 1). Of these, 11 are readily available and the remaining 7 have been replaced by newer formulations without cancellation of their registrations. A further 2 *B.t.* products have registrations pending.

Prior to 1980, only three companies produced *B.t.* Currently, at least 17 companies are involved in some aspect of *B.t.* technology. Eleven produce

Table 2. Operational use of *B.t.* against forest insect pests in Canada in the last 6 years (total hectares treated).

Year	Spruce budworm	Jack pine budworm	Eastern hemlock looper	Gypsy moth
1985	675,694	248,676	2,365	170
1986	351,107	482,032	5,420	103,094
1987	397,061	105,463	4,183	40,249
1988	432,587	0	23,788	13,784
1989	304,948	4,763	5,361	12,951
1990	695,539	0	9,983	33,956
Total	2,856,735	840,934	51,100	204,186

conventional *B.t.* spray products, 4 are involved in improving strains by genetic manipulation and 8 are involved with inserting a *B.t.* toxin gene into plants in order to develop insect resistant plants. These topics are discussed later.

Use of *B.t.* in Canadian forests The first aerial spray trials with *B.t.* in Canada in 1960 were on western black-headed budworm, *Acleris gloverana* (Walshingham), in British Columbia (Kinghorn et al. 1961) and spruce budworm in New Brunswick (Mott et al. 1961). Most of the early research was conducted on spruce budworm in the 1970's. Efforts intensified in 1977, when a collaborative agreement was signed between the Canadian Forestry Service and the USDA Forest Service to accelerate research on spruce budworms. The program, named CANUSA, was in place over a 5 year period, and involved all aspects of budworm research including control methods. The progress in development of *B.t.* as an operational alternative to chemical pesticides was reviewed by Cunningham (1985a).

In 1978, the recommended dosage of *B.t.* for control of spruce budworm was 20 Billion International Units (BIU) in 4.7 L/ha. After further field trials, this dosage was considered marginal and changed from 20 to 30 BIU and, with the development of more concentrated spray products, was applied in lower emitted volumes of 1.6 to 2.4 L/ha. The effectiveness of a pesticide depends on the number of droplets per unit area, the dosage in each droplet and how many droplets a larva ingests, i.e. its feeding activity. The trend has been towards high potency *B.t.* formulations applied at low volumes which gives a lethal dosage of toxin in each droplet. A model developed at the Forest Pest Management Institute established that one 50 μm droplet per balsam fir needle of a 12.7 BIU/L product will give effective control of spruce budworm (Fast et al. 1986; Lambert 1987). Lower dosages can cause feeding inhibition from which larvae can recover if no more *B.t.* is encountered (Fast and Regnière 1984; van Frankenhuyzen and Nystrom 1987).

Between 1979 and 1983, *B.t.* was used to treat 1 to 4% of the area sprayed for control of spruce budworm in eastern Canada; the remainder was sprayed with the chemical insecticides Fenitrothion® or Matacil®. This figure increased to 20% in 1984, climbed to 63% in 1988, dipped to 39% in 1989 and again reached 63% in 1990. The areas treated with *B.t.* to control spruce budworm in eastern Canada between 1985 and 1990 are shown in Table 2. New Brunswick is the only province still using Fenitrothion. Matacil, although still registered, is no longer being produced because of low sales volumes. The overall Canadian figure for *B.t.* use is significantly affected by the fact that New Brunswick treats large areas.

B.t. is also used operationally on jack pine budworm, *C. pinus pinus* Freeman, eastern hemlock looper, *Lambdina fiscellaria fiscellaria* (Guenée), gypsy moth, *Lymantria dispar* (L.) and forest tent caterpillar, *Malacosoma disstria* Hübner. Areas treated in the last 6 years are shown in Table 2. By far the largest use has been for spruce budworm. Jack pine budworm and gypsy moth sprays have been limited to Ontario, and eastern hemlock looper sprays to Newfoundland. All *B.t.* products for forestry use are registered for spruce budworm, but it is necessary to read the labels to establish which products are registered for other species of defoliating insect pests.

Environmentalists consider synthetic chemical pesticides unacceptable for forest management and have used considerable political pressure to force a substitution of biological control agents for synthetic chemical pesticides. Because *B.t.* is the only biological control agent that is commercially available in sufficient quantities to treat large areas of forest, it is the only alternative to abandoning forests to the ravages of defoliating insect pests.

Cost of *B.t.* Bidding for forestry contracts is highly competitive and the cost of *B.t.* has been fairly constant at between 35¢ and 40¢ per BIU for the last few years. The use of higher potency formulations has reduced aerial application costs because fewer lifts are required to treat a given area. In 1988, the applied cost of *B.t.* on spruce budworm (product plus aircraft cost) was $23.02/ha in Quebec and $21.30/ha in New Brunswick. Chemical insecticides cost less than *B.t.*, but this differential has been decreasing steadily. In Quebec, *B.t.* for spruce budworm control was 4.5 times more expensive than chemical insecticides in 1981 and this dropped to 1.7 times in 1985 when chemical insecticide use was discontinued in Quebec. In 1988, the figure was 1.2 times in New Brunswick.

Problems with *B.t.* *B.t.* has a narrower window for timing spray applications than chemical pesticides, is not as effective as chemical pesticides at high insect population densities, is slower acting and is more susceptible to post-spray weathering of the deposit. All these factors add up to the fact that *B.t.* is more difficult to use than chemical pesticides and there is a higher incidence of unacceptable defoliation following application of *B.t.* than application of chemical insecticides.

B.t.k. affects only Lepidoptera, whereas broad spectrum synthetic chemical insecticides have an impact on virtually every arthropod that is active in the forest at the time of application, including beneficial insects such as parasites, predators and pollinators. However, some criticism has been levelled at *B.t.* because it may affect non-target Lepidoptera, which are important in food chains, are aesthetically attractive or are listed as endangered species.

Genetic manipulation of *B.t.* Because *B.t.* toxin genes are located on plasmids, they can be easily isolated and cloned. About 50 toxin genes have now been cloned and sequenced. There are basically two approaches to the genetic engineering of *B.t.* The first is to modify the toxin itself, and the second is to transfer the toxin gene to another microorganism or to the host plant of the target insect species.

When modifying the toxin, it may be possible to tailor specificity, increase toxicity and enhance persistence. Some of these aspects have been accomplished. In a product called Condor, Ecogen Inc. used a naturally occurring plasmid transfer mechanism, conjugation, to combine toxin genes from two strains into one *B.t.* and thus tailor specificity to forest pest species (Carlton et al. 1990). Persistence has been increased in a Mycogen Corporation product called MVP™ Bioinsecticide where a *B.t.* gene is expressed in *Pseudomonas fluorescens* Migula which does not lyse at the end of the fermentation cycle. The *Pseudomonas* is then killed and cross-linking of the cell wall enhances persistence of the *B.t.* toxin (Gelernter 1990). Strains of *B.t.* have been developed which contain both the coleopterous and lepidopterous active toxins and can be used against a wider range of crop pests, such as those found on potatoes (Carlton et al. 1990).

The transfer of toxin genes may have interesting applications in forestry. The toxin gene may be put into another microbe which is found in the same habitat as the pest species and will be ingested along with food. The *B.t.* toxin was engineered into a root colonizing *Pseudomonas* in 1983 as a control for larvae which eat the roots of corn plants. The *B.t.* toxin gene can be used to enhance other pathogens and there are three instances where it has been inserted into the genome of a baculovirus thus increasing the specificity of the *B.t.* Perhaps the most exciting aspect of all is development of transgenic plants. The *B.t.* gene was first transferred into tomato and tobacco plants in 1985 using the crown-gall bacterium *Agrobacterium tumefaciens* Smith and Townsend as a natural gene transfer system (Vaeck et al. 1987). The *B.t.* gene was recently transferred into a *Populus* sp. and tests have been conducted with forest tent caterpillar. Several Canadian establishments are working on the transformation of conifers. However, the development of transgenic plants expressing the *B.t.* toxin is not without risk. There may be an unpredictable evolutionary response due to the complexity and longevity of the forest ecosystem (Raffa 1989). Pest species constantly exposed to *B.t.* toxin may develop resistance to it, or non-pest species unaffected by *B.t.* may fill the niches occupied by the pests of today and become the pests of tomorrow.

VIRUSES

Mode of action Viruses only grow in living cells and it is necessary to propagate them either in host insect larvae or in insect cell culture. Presently, propagation in host larvae (in vivo) is the only practical method of large scale production, although there is intensive research on production in cell cultures (in vitro). Nine different groups of insect viruses are known to infect insects (Entwistle and Evans 1985), but only two types of baculoviruses have been used to any extent for microbial control. These are nuclear polyhedrosis viruses (NPV) and granulosis viruses (GV).

Baculoviruses have rod-shaped virus particles and their nucleic acid is circular, double-stranded DNA. NPVs and GVs have virus particles contained within inclusion bodies; there are many virus particles in NPV inclusion bodies and one, or rarely two, in GV inclusion bodies. These inclusion bodies protect the virus particles and make them more stable than naked virus particles. Baculoviruses have been isolated mainly from Lepidoptera and Hymenoptera, but a few have also been reported from Diptera, Coleoptera, Neuroptera, Trichoptera and Crustacea. Baculoviruses are highly to moderately host-specific. Many are known to infect only one species. The NPV of the alfalfa looper, *Autographa californica* (Speyer) has the widest known host range and has been reported to infect 43 species of Lepidoptera in 11 families (Payne 1986).

Like *B.t.*, baculoviruses have to be ingested to cause infection. The inclusion body protein dissolves in the alkaline larval gut juice and the virus particles are released. The virus particles infect gut cells in susceptible species and then usually spread to other organs. In the final stage of infection, more inclusion bodies are produced in infected cells. When larvae die, massive quantities of infectious inclusion bodies are released into the environment. They may infect other larvae (horizontal transmission) or the next generation of larvae (vertical transmission). Large quantities of inclusion bodies accumulate in the soil where they can retain some viability for long periods of time. Soil is almost certainly the reservoir for baculoviruses when the insect host is absent.

Advantages and disadvantages of baculoviruses The high degree of specificity of baculoviruses makes them very attractive from an environmental standpoint, but less attractive commercially than *B.t.*, which can be used to control a wider range of agricultural and forestry pests. Baculoviruses are slower acting than *B.t.* and when applied against forest pests in Canada take weeks, as opposed to days, to kill the target pest. The timing of application of baculoviruses is even more critical than for *B.t.* and, ideally, baculoviruses should be applied as early as possible after eggs have hatched and larvae have commenced feeding. The tremendous advantage of viruses is that secondary infection may occur when healthy larvae ingest inclusion bodies released from virus-killed larvae and viral epizootics can develop. Also, viruses can persist from year to year and infect the next generation of larvae.

Use of viral insecticides Field trials have been conducted with viruses on 19 species of forest insect pests in Canada, 11 of which were Lepidoptera and 8 Hymenoptera. Aerial spray trials have been conducted on 8 species and the remainder were ground spray trials (Cunningham and Entwistle 1981; Cunningham 1982). Three viral insecticides were registered in Canada in 1983, two of them for control of Douglas-fir tussock moth, *Orgyia pseudotsugata* (McDunnough), and the third for redheaded pine sawfly, *Neodiprion lecontei* (Fitch). Registration petitions have been submitted for NPVs to control European pine sawfly, *N. sertifer*, and gypsy moth (Table 3).

Douglas-fir tussock moth is a cyclical pest in British Columbia and the last outbreak terminated in 1983. Two viral insecticides are registered in Canada for this pest, but neither has been used operationally. Virtuss is produced in whitemarked tussock moth larvae at the Forest Pest Management Institute and TM BioControl-1 is produced by the USDA Forest Service in Douglas-fir tussock moth larvae. The latter is also registered in Canada to facilitate importation by the British Columbia Forest Service which has sufficient TM Biocontrol-1 on hand to treat 8,000 ha and sufficient Virtuss to treat 1,400 ha. It is expected that these viral insecticides will be used in 1991 when the next outbreak is forecast. Virtuss is also effective against whitemarked tussock moth, *O. leucostigma* (Smith), and has been field-tested in Newfoundland.

Redheaded pine sawfly is a pest of red pine and jack pine plantations in eastern Canada. Experimental spray trials were conducted between 1976 and 1983

Table 3. Viral insecticides registered in Canada by the Forest Pest Management Institute or with registrations pending.

Product	Year registered	Target pest species	Dosage (polyhedral inclusion bodies/ha)	Number of larvae to produce a 1 ha dosage
Lecontvirus	1983	Redheaded pine sawfly	5×10^9	50
Virtuss	1983	Douglas-fir tussock moth	2.5×10^{11}	200
TM BioControl-1*	1983	Douglas-fir tussock moth	2.5×10^{11}	200
Sertifervirus	Pending	European pine sawfly	5×10^9	50
Disparvirus	Pending	Gypsy moth	5×10^{11} (twice)	400

*Produced by the USDA Forest Service

with a viral insecticide called Lecontvirus prior to its registration in 1983. Between 1976 and 1990, 590 plantations with a combined area of 4,900 ha were treated from the air and from the ground. This is the only viral insecticide which has been used operationally in Canada.

Spruce budworm, western spruce budworm, *C. occidentalis* Freeman, and jack pine budworm are all susceptible to the same virus diseases. Spruce budworm has been extensively studied because of its economic importance and between 1971 and 1983, 65 plots with a combined area of 2,656 ha were treated with viruses. Mainly NPV was applied, but GV and entomopoxviruses were also tested (Cunningham 1985b). Between 1976 and 1982, 6 plots with a combined area of 424 ha were treated with NPV or GV to control western spruce budworm and in 1985, one 50 ha plot was treated with NPV to control jack pine budworm.

Virus epizootics have never been observed to terminate budworm outbreaks and attempts to initiate epizootics have been only partially successful. Traditionally, microbial and chemical control agents are applied on budworms at budflush, by which time larvae have reached their fourth instar. Before budflush, larvae are concealed and protected from any spray deposit. When fourth instar larvae become infected with NPV or GV, they are close to pupation before they die. There is no foliage saved and there is no time for horizontal transmission of the virus. Vertical transmission does occur from one year to the next, but the impact of the virus is diluted over time. Registration of wild-type spruce budworm viruses has not been pursued. However, the economic importance of these species makes viruses prime candidates for genetic manipulation.

European pine sawfly NPV was discovered by Dr. F.T. Bird in 1949 (Bird 1953) and extensively used in the 1950's and 1960's to control this major pest of Christmas tree plantations. Unfortunately, no records were kept of areas treated. European pine sawfly is currently a minor pest in Canada. Between 1975 and 1990, only 4 plantations, with a combined area of 160 ha, were experimentally treated with this virus. A registration petition for an NPV product called Sertifervirus has been submitted to Agriculture Canada and is currently being evaluated.

Gypsy moth was not a major pest in Canada until 1981. Between 1982 and 1990, 22 plots, with a combined area of 415 ha, were treated with gypsy moth NPV products, either Gypchek, produced by the USDA Forest Service, or Disparvirus, produced by the Forest Pest Management Institute. A registration petition for Disparvirus was submitted to Agriculture Canada in 1990. Results from gypsy moth virus spray trials have been most encouraging and this virus is considered a prime candidate for commercialization.

Production of entomopathogenic viruses Commercial production of viral insecticides has been a major hurdle to their widespread use and acceptance. Most viral insecticides available to date have been produced in government laboratories. Insecticide manufacturers do not want to rear insects in order to produce viral insecticides. However, if in vitro production in insect cell cultures can be accomplished at a realistic price, many pharmaceutical companies with expertise in vaccine production may be interested in manufacturing viral insecticides.

Labour costs in developed countries make production of viral insecticides in insect larvae prohibitively expensive. An exception to this rule are sawfly viruses which can be produced in heavily infested plantations. Both redheaded pine sawfly and European pine sawfly are gregarious species and diseased and dying colonies can easily be harvested and processed (Cunningham and McPhee 1986). However, viral insecticides from lepidopterous species must be produced in laboratory reared larvae. Mechanized insect handling and robotics could substantially reduce costs and two companies are interested in this approach to marketing realistically priced viral insecticides. These companies are Espro in Maryland, USA and Calliope in Béziers, France. Both see gypsy moth NPV as a potentially lucrative product.

Genetic manipulation of viruses Baculoviruses have been extensively studied at the molecular level, the genomes of several viruses have been mapped and some individual genes identified, cloned and sequenced. Alfalfa looper NPV is the most intensively studied baculovirus. The gene which codes for the major inclusion body protein of baculoviruses is strongly expressed; it can be deleted and replaced by an exogenous gene which is also strongly expressed (Smith et al. 1983). To date, about 140 foreign genes have been inserted into this site by many different research teams. Most of these proteins have been of medical or veterinary significance, but the technology is available for development of enhanced viral insecticides.

A possible method of improving the effectiveness of baculoviruses as insecticides is the insertion of foreign genes which encode for insect-specific toxins, hormones, or other proteins which may disrupt metabolism (Kirschbaum 1985). The first environmental release of a genetically manipulated baculovirus was in 1986 in the UK using alfalfa looper NPV with a genetic marker (Bishop 1986). Recently, a *B.t.* toxin gene was expressed in this virus (Merryweather et al. 1990). There is also a great deal of interest in determining which baculovirus genes influence host specificity and virulence with a view to manipulating these genes.×

Several other baculovirus genomes have been mapped; those of potential use for control of forest insect pests include spruce budworm NPV (Arif and Doerfler 1983; 1984), Douglas-fir tussock moth NPV (Leisy et al. 1984) and gypsy moth NPV (Smith et al. 1988). Attempts are being made to enhance the effectiveness of these viruses against their insect hosts. Genetic manipulation of insect viruses is not limited to baculoviruses and foreign genes have also been expressed in entomopoxviruses and densoviruses.

REGISTRATION

A new set of guidelines for registration of microbial pesticides in Canada has recently been released by Agriculture Canada. This document covers all pesticides including such agents as avicides, piscicides and aquatic herbicides as well as insecticides. Registration petitions should be examined on a case-by-case basis and it is hoped that numerous exemptions will be made for well-documented and researched agents that have a good data base and a history of safe and effective use. Genetically manipulated products should not cause undue concern, provided that the vector is well-researched and documented and that any foreign material inserted into this vector is likewise well-researched and considered safe to both man and the environment. A rash of new genetically altered products with industrial applications, such as the cleaning up of oil spills, is greatly outnumbering microbial insecticide products.

Unfortunately, registration of microbial insecticides under the Pest Control Products Act is still a deterrent to small companies that may wish to enter this field. The cost of registration of a microbial agent is only a fraction of the cost of registration of a chemical pesticide, but is still a major commitment, especially when protocols are not available for all the required tests and the outcome of the review of a registration submission is uncertain.

NETWORKS

Research networking is a highly effective method of accelerating the development of new products and processes. There are three networks in Canada involved in the development of microbial insecticides. Biocide was founded by Dr. P.G. Fast of the Forest Pest Management Institute in 1984 and involves developing improved *B.t.* products for forest insect pests and particularly for control of spruce budworm. The National Research Council of Canada, the Forest Pest Management Institute and two universities are in this network. MicroBioNet, established in 1988 under the direction of Dr. Basil Arif of the Forest Pest Management Institute, encompasses mainly the genetic manipulation of insect viruses, although microsporidia may also be involved. There are 13 collaborators in four university departments and in the National Research Council as well as one industrial partner. Insect Biotech Canada, established in 1989 under the scientific direction of Dr. G.R. Wyatt, is a research network centred at Queen's University. It is funded by the Government of Canada under the Networks of Centres of Excellence Program and involves 24 scientists from 10 universities and two government laboratories, including the Forest Pest Management Institute. There are two industrial partners. There are five main thrusts to this program, the principal one being the molecular engineering of baculoviruses.

CONCLUSIONS

In the heyday of synthetic chemical pesticides, a product developed by multinational corporations was targeted at a multi-million dollar market. In Canada, about 5% of insecticides are used in forestry and the remainder in agriculture and public health programs. No chemical pesticides were tailored to the Canadian forestry market and insecticides for major global pests were screened against Canadian forest insects, particularly spruce budworm, and the promising candidates developed.

This situation has changed radically and many small companies, satisfied with niche markets, are involved in the development of microbial control agents, as well as the multinational corporations. The Canadian research networks are focusing their efforts on spruce budworm and other serious forest insect pests. With the combined efforts of industry, government and university laboratories, it is probable that several new, naturally occurring or genetically engineered *B.t.* and viral insecticide products will soon become available for field testing.

It is unlikely that any fungi or microsporidia will be developed for the forestry market in the near future. There is little experience in registering such products in Canada and microsporidia, like viruses, must be produced in host insect larvae. Naturally occurring fungal epizootics periodically devastate forest insect populations. Some fungi can be produced easily in liquid culture. Fungi infect insects by penetrating the cuticle, as opposed to the ingestion route of *B.t.*, viruses and microsporidia. However, there are many problems to be resolved before widescale use of mycoinsecticides is feasible for forestry application.

Nematodes have been applied operationally only to agricultural crops but they may have some application in forestry. Several companies market nematode products in the USA. Nematodes are not host-specific and will attack a wide range of insect larvae. They are attracted to larvae by a carbon dioxide gradient and enter them by the mouth or anus. To date, aerial application of nematodes has not been feasible due to desiccation before reaching the target insect pest. However, they could be applied to soil-dwelling insects which are pests of tree nurseries, and there may be other specialized forestry applications for nematodes.

There is a strong public demand for the use of biological and microbial control agents in preference to synthetic chemical insecticides. However, the development of microbial control agents has been a slow process. It took 30 years for *B.t.* to become a viable pest management tool. Hopefully, development of other microbial control products can be accelerated with increased funding for research and with a sympathetic and enlightened approach on the part of pesticide regulatory authorities.

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Biological Control of Plant Diseases

M.S. Reddy
Esso Ag Biologicals, 402-15 Innovation Blvd., Saskatoon, Saskatchewan S7N 2X8

ABSTRACT *Plant diseases caused by soil-borne pathogens have obstructed efforts to increase agricultural crop productivity. Adequate chemical control of these pathogens has not been achieved. Furthermore, total dependence on fungicides having site-specific activities is undesirable, not only due to their high cost, but because fungi quickly develop resistance with continued exposure. Intense use of fungicides also increases environmental pollution, health hazards, and can be phytotoxic. Both private and public sector concerns regarding the use of chemicals have given a new impetus to research towards plant disease control by the introduction of beneficial rhizobacteria. The mechanisms by which beneficial microorganisms are considered to enhance plant growth include promotion of the availability and uptake of nutrients, production of plant growth regulators and suppression of soil-borne pathogens. Evidence is increasing that plant growth promoting rhizobacteria (PGPR) have the potential to increase plant growth or crop yields significantly by suppressing soil-borne pathogens. The potential applicability of microbial products for biocontrol of root disease is discussed.*

INTRODUCTION

Plant diseases caused by many microbial pathogens play an important direct role in the diminution of natural resources for agriculture. These diseases have obstructed efforts to increase crop productivity. In spite of significant progress in plant breeding and other disease management techniques, losses due to diseases remain a major factor limiting agriculture in many parts of the world including Canada. The practising agriculturist is commonly concerned with understanding how plant pathogens cause crop losses and how they can be controlled.

Plant root health in nature primarily depends upon both the inherent resistance of a plant to microbial attack and the biological equilibrium between competing beneficial and deleterious microorganisms in the rhizosphere as mediated by the environment (Schroth et al. 1984, Schippers et al. 1987). Rhizosphere bacteria play a major role in this equilibrium by their interactions with various pathogenic agents such as fungi, bacteria, nematodes, algae, viruses and viroids. The potential of certain microbes to affect plant growth has long been recognized. Microorganisms such as nitrogen fixing bacteria, mycorrhizae, and antagonists to pathogens are important determinants of plant growth. In addition the physiological activities of bacteria in the rhizosphere affect the availability of nutrients, and produce compounds which have growth regulator activity in plants. Opportunities for improved plant growth are offered through manipulation of the microflora of the rhizosphere (Reddy and Rahe 1989a, 1989b). Efforts toward this end has been intensified in recent years. Hiltner, in 1904, observed that plant roots supported populations of bacteria in numbers far exceeding those in soil a few millimetres away. He proposed the word "rhizosphere" for the area of intense biological activity immediately adjacent to the root. As part of a review of rhizosphere research, the Agriculture Canada Research Branch in Ottawa hosted a workshop in October 1989 for the first time in Canada. This workshop brought scientists together from federal and provincial governments, universities and industries. They mainly discussed the fields of mycorrhizae, nitrogen fixation and other soil-microbial interactions. This area is of particular interest to plant pathologists in that it is also the site where soil-borne pathogens are stimulated by root exudates to undergo pre-infection processes.

Biological control of plant diseases is a fascinating, challenging, and also sometimes frustrating area of research. More than 60 years ago, the basic ideas on the use of microbial inoculants in biological control were established (Campbell 1989). Until the 1960's, these remained largely with experimental development rather than with field-oriented research work. Basically, this research is overshadowed by the enormous development of chemical fungicides during and immediately after World War II. During 1963 Dr. J. Rishbeth demonstrated use of the fungus *Peniophora gigantea* (Fr.) Massee to control stem and butt rot of conifers caused by *Fomes annosus* (Fr.) Karst. It was one of the first biological control agents for commercial use against a plant disease and it remains in use today. Since that time there has been an enormous amount of research devoted to biological control (Cook and Baker 1983). Many biological control efforts have involved the use of fungal antagonists, and the results of these efforts has been highly variable. Bacteria capable of utilizing root exudates as their primary source of nutrition have distinct advantages in biological control over soil fungi, since they can be added directly to the plant in the form of root dips or soil or seed treatments (Brown 1974).

Currently, many biotechnology companies have programs to develop biological control agents as commercial products. The increase in interest by government agencies, universities and commercial companies is in part a response to public concern withthe hazards associated with chemical pesticides. It is also as a result of increased knowledge of microbial ecology and the availability of genetic engineering technology for identifying and tracking strains of microbes associated with plant roots. Moreover, the inordinately high cost of developing chemicals to control plant diseases, and the lack of resistance of crop plants to many diseases, has attracted the attention of many venture capital companies that foresee a profitable future (Lethbridge 1989, Macdonald 1989). My intent is to critically examine the status of current biological control studies on plant diseases in Canada, to question approaches, to separate fact from speculation, and to address some principles and hypotheses. In particular, I will focus here on the use of antagonists, mainly rhizobacteria, to control root infecting fungal pathogens, because bacterial seed treatments have shown to control plant diseases and provide other benefits to agricultural crops (Brown 1974, Cook and Rovira 1976, Lifshitz et al. 1987, Lumsden and Locke 1989, Perumalla et al. 1990, Reddy and Patrick 1989, 1990, Reddy and Rahe 1989a, 1989b, Reddy et al. 1990, Schroth et al. 1984).

PRESENT STATUS

In the last 15 years, several examples of bacteria capable of providing successful disease control in the field have been reported. But my coverage here is given only to those biological control reports that have been adopted commercially or where there is clear evidence that research and development, supported by several years of replicated field tests, has progressed to a stage where commercial exploitation is a serious probability.

In Canada groups are actively engaged in biological control of soil-borne root diseases of many agricultural crops, using mainly beneficial bacteria, at universities (McGill University, University of Toronto, University of Guelph, University of Alberta, Simon Fraser University and University of Saskatchewan), within the federal government (most Agriculture Canada Research Stations), provincial governments (Alberta Environmental Centre, Ontario Ministry of Food and Agriculture), and industries (Esso Chemical Canada, Philom Bios, British Columbia Research Corporation and Premier Peat).

There are numerous reports of control of plant diseases in the literature. Bacteria shown or thought to have potential for biological control occur in many genera including *Agrobacterium*, *Arthobacter*, *Azotobacter*, *Bacillus*, *Enterobacter*, *Flavobacterium*, *Serratia* and *Pseudomonas* (Weller 1988). These bacterial groups may be considered beneficial to many crop plants. Most notable is *Agrobacterium radiobacter* (Beijernick and van Delden) strain 84, which provides effective biological control against crown gall of several woody plants and is used world-wide (Burr and Caesar 1984). Interest in the use of other bacteria is growing. The intriguing area of current research deals with application to seeds, tubers, roots or soil causing growth stimulation of the plants in field soil. These have recently been termed plant growth-promoting rhizobacteria (PGPR) (Kloepper et al. 1980).

The Ag Biologicals group of Esso Chemical Canada, located in Saskatoon, is one of the largest agricultural biologicals companies in North America having recently taken over the Microbial Inoculant Business Unit of Allelix Crop Technologies. The group has a large number of bacterial strains in their culture collection capable of aggressively colonizing growing root systems and providing beneficial attributes including enhanced seedling emergence and increased plant biomass and yield (Kloepper et al.

Table 1. Examples of microbials that are available commercially for biological control of plant diseases.

Antagonist	Disease	Pathogen	Crop
Agrobacterium strain 84	Crown gall	*A. tumefaciens*	Horticulture
Peniophora gigantea	Butt rot	*Heterobasidium annosum*	Conifers
Trichoderma spp.	Damping-off seedlings	*Pythium, Phytophthora*	Many crops
Bacillus subtilis A-13	Seedling diseases	Many pathogens	Peanuts
Pseudomonas fluorescens	Seedling diseases	Many pathogens	Cotton

1988, 1989, Tipping et al. 1990, Reddy et al. 1990).

Table 1 lists the microbials that are available commercially as biological control agents. Most of the examples are for soil-borne, rather than foliar, diseases. The main reason for this is that foliar diseases are often controlled by effective fungicides or by varietal disease resistance. Foliar diseases are the first target for control because they were the main limitation on plant productivity and they can be easily recognized. Root diseases, particularly root rots and pre- and post-emergence damping-off diseases caused by *Fusarium* spp., *Pythium* spp., and *Rhizoctonia* spp., are now seen as a major constraint or threat to many horticultural or field crops and their control is receiving much more attention (Cook and Baker 1983, Sivamani and Gnanamanickam 1988, Weller 1988). Biological control on a major scale is a good possibility and is being actively developed.

A further factor in the success of microbials is that they are often designed to give protection for short periods of time. It is relatively easy to have an antagonist control diseases such as root rots and damping-offs.

Pseudomonas spp. were not used extensively in bacterization experiments until recent years when their potential as PGPR was demonstrated. As biological agents, *Pseudomonas* spp. have been successfully used in laboratory, greenhouse and field experiments. *Pseudomonas* have also been shown to suppress various pathogens (Kloepper et al. 1980, Reddy et al. 1990, Sivamani and Gnanamanickam 1988, Suslow1982, Suslow and Schroth 1982, Tipping et al. 1990, Weller 1988).

It is the objective of this presentation to review the current status of biological control of plant diseases and to analyze the significance and potential uses of the microbials in the future. Specifically, I will discuss the phenomenon of growth promotion with respect to disease control using beneficial PGPR. Possible modes of action and variable responses in the greenhouse and during field testing will also be discussed.

IMPORTANCE OF BIOLOGICAL CONTROL OF PLANT DISEASES

It is important to consider why we are concerned with plant disease controls using microbials. As can be seen in Table 2, it is clear that microbials have some advantages over chemicals (Lethbridge 1989). One of the often quoted advantages of microbials over chemicals is that the microbials are less prone to problems of resistance. The development of pathogens resistant to fungicides and bactericides has now become a major problem globally. Fungal pathogens resistance to fungicides are well known (Cook and Baker 1983): for example *Venturia inaequalis* (Cooke) Wint. (causal agent of apple scab), *Erysiphe cichoracearum* DC (causing powdery mildew of cucurbits), *Botrytis cinerea* Pers. (causing diseases on several plants) are resistant to benomyl; *Phytophthora infestans* (Mont.) de Bary (causing late blight of potato) is resistant to metalaxyl; *Erysiphe graminis* DC.:Fr.(causing powdery mildew of wheat) is resistant to triadimeton; *Helminthosporium avenae* Eidam (causing foot rot of oats) is resistant to organomercurials. Therefore, fungicides have to be used as mixtures with other chemicals, intermittently or alternately, to avoid selection for resistant strains. Microbials, on the other hand, often possess multiple antagonistic traits so that single gene mutations in the fungal pathogen are not sufficient to provide resistance.

PRINCIPLES AND MECHANISMS

Both direct and indirect mechanisms have been suggested to explain the positive influence of certain bacteria on plant growth and disease control (Reddy and Rahe 1989). Hypothesized direct mechanisms are that bacteria exude substances that stimulate plant growth such as nitrogen, plant growth hormones and compounds that promote the availability of phosphates in the root zone (Brown 1974, Lifshitz et al. 1987). A popular hypothesis for an indirect mechanism is that populations of various pathogenic and deleterious microorganisms that affect the root system are reduced by displacement after introduction via seed, soil or root bacterization (Kloepper and Schroth 1981, Reddy and Rahe 1989, Suslow 1982, Suslow and Schroth 1982).

In biological control of plant pathogens, "Antagonists are biological agents with the potential to interfere in the life processes of plant pathogens" (Cook and Baker 1983). Antagonists include: fungi, bacteria, nematodes, protozoa, viruses and viroids. Antagonists are the equivalent of "natural enemies" used in entomology. Antagonism expressed in different ways includes antibiosis, parasitism, competition and induced resistance.

Antibiosis Antibiosis is defined as the inhibition or destruction of one organism by a metabolite of another. These metabolites (antibiotics) represent a second type of compound of potential importance in plant growth promotion and biological control.

Biocontrol agents used in agriculture likely will interact with pathogens by the way of antibiosis. In vitro antibiotic activity was generally correlated with the ability of strains which suppress or control diseases *in vivo*. For example, Agrocin 84 is a kind of antibiotic which mediates suppression of *Agrobacterium tumefaciens* (Smith and Townsend) by *A. radiobacter* strain 84 in wounded tissue (Burr and Caesar 1984, Cook and Baker 1983). Another example is phenazines which are produced by some specific strains of fluorescent pseudomonads suppressive to take-all of wheat (Cook and Rovira 1976, Weller 1988). Also the Esso group and other researchers have demonstrated that the purified antibiotics pyoluteorin and pyrrolnitrin, produced from *Pseudomonas fluorescens* Migula pf.5, provided control of damping-off of cotton caused by *Pythium ultimum* Trow or *Rhizoctonia solani* Kuehn. There are many similar examples listed in the literature.

Siderophores are chelating compounds with a special affinity for iron which have received considerable attention as a possible mode-of-action for biological control agents (Swinburne 1986). There are examples, usually with *Pseudomonas* spp., where siderophore production seems to be a major role in biological control, depriving the pathogen of iron and making it grow more slowly or not at all. In *Fusarium oxysporum* Schlecht. f.sp. *lini* the *Pseudomonas* siderophore inhibits chlamydospore germination and hence reduces disease. Some biocontrol pseudomonads produce siderophores and antibiotics and both seem to be necessary for the full action of the organism (Swinburne 1986).

Competition for nutrients Competition occurs between organisms for nutrients and available space where conditions are suitable for growth. Competition for nutrients supplied by root and seed exudates probably occurs in most interactions between bacteria and pathogens on the root. Populations of bacteria established on planting material or roots become a partial sink for nutrients in the rhizosphere. Fluorescent pseudomonads are suited for this because they are nutritionally versatile and can grow rapidly in the rhizosphere.

Parasitism Some of the best known fungal antagonists kill pathogens by parasitism. *Trichoderma* has been shown to control some *Pythium* spp. by mycoparasitism (Chet 1987). *Sporidesmium* or *Coniothyrium* attack sclerotia of *Sclerotium cepivorum* Berk., *S. sclerotiorum* (Lib.) de Bary and *Sclerotinia minor* Jagger. These mycoparasites are successful at reducing the fungal inoculum in the soil with or without a host (Ayers and Adams 1981).

Induced resistance This refers to the enhanced levels of resistance to disease following inoculation of a plant with the pathogens or treatment with chemicals. Induced resistance occurs in many plant families. Heat-killed cells, cell walls and culture filtrates of pathogens as well as live pathogens are effective inducers of resistance in their host plant. Current research at the Agriculture Canada Research Centre in London, Ontario, in collaboration with the Esso group, has shown that application of rhizobacteria to white bean results in induction of disease resistance to root rot fungus *Fusarium* spp. This suggests the mode of action of biological control via the production of phytoalexins, which are fungi-toxic isoflavonoids.

Plant growth regulators Several research papers indicated that several strains of *Bacillus*, *Azotobacter*

Table 2. Advantages and disadvantages of microbials compared to chemical fungicides (data from Campbell 1989).

	Chemical	Microbial
Costs/benefits		
Research and development	US$ 20m	US$ 0.8–1.5m
Market size required for profit	US$ 40m/year	US$ 1.5m/year
Toxicological data	US$ 10m	US$ 0.5m
Patentability	Well established	Still developing
Discovery	Screen 15,000 compounds to identify one product	Rational selection for specific target disease
Efficacy		
Spectrum of activity	Generally broad	Generally narrow
Resistance	Often develops	Not known
Type of action	Both preventive and curative	Only curative
Safety		
Operator safety	Chemicals can be hazardous	Low operator risk
Environmental impact	Accumulation in food chains	Low to non-existent
Residues	Interval before harvest often required after application	Crop can be harvested immediately

and *Pseudomonas* spp. are able to produce plant growth regulators such as auxins, cytokinins and gibberellin-like compounds in culture (Brown 1974). These substances are responsible for some plant growth responses. For example growth effects on canola plants treated with some selective strains of *Pseudomonas* spp. can be mimicked by PGR. A growth stimulation of cucumber and tomato was also noted following seed inoculation with these strains. Some strains that are able to produce these PGR and stimulate plant growth responses are also able to protect seedlings from pre- and post-emergence damping-off diseases caused by *Pythium* or *Rhizoctonia* spp. (Reddy, unpublished data). However, it is difficult to draw conclusions as to the likelihood of this phenomenon occurring in the field.

FACTORS AFFECTING PERFORMANCE

Formulation of Biological Control Agents Formulation is very important and should not be overlooked. It converts microbials into commercial products. It has a marked effect on product performance. In fact, chemical formulations have set high standards with regard to long shelf-life and microbial formulations will be expected to match them. Loss of viability during storage must be kept to a minimum. A shelf-life of at least one year at room temperature with stability over the range of –5°C to 30°C are generally demanding requirements for most types of microbials. One advantage of formulating microbials like chemicals is that they can be applied using standard machinery. Many soil factors such as temperature, soil moisture, and clay content influence the survival and establishment of the bacteria and their influence on the pathogen. Peat and other carriers developed for *Rhizobium* may be useful to other microbials.

Inconsistent Performance A multitude of factors could account for inconsistent results. The ability of a bacterium to compete and survive in nature is very important. One must consider microbial inoculants, especially those involved in biological control of pathogens, to be a form of crop insurance. Benefits are only realized when pathogen populations are sufficient to cause reduced yields. Given uneven distribution of pathogen populations, positive yield responses will be difficult to demonstrate within a given field, let alone between distinct geographic locations. Repeated culturing of a bacteria in vitro can result in a loss of field efficacy, possibly related to reduction in antibiotics or other metabolites. Quality control and constant strain evaluations are absolutely required.

Geographic Variability The biocontrol agents used at one specific geographic location may not do well in other areas. To overcome this problem, large scale field trials should be conducted at different geographic locations in order to evaluate the potential of applicability of the microbials under different environmental conditions. The efficacy test also provides data on the optimum conditions necessary for the use of biological pesticides.

Root Colonization Root colonization by introduced microbials is essential for biological control (Weller 1988). Variable root colonization from plant to plant, or root to root on a given plant, is a probable reason for inconsistent control of plant diseases. However, no strict guidelines exist for root colonization, and establishment of one standard that will fit all biological control agents is difficult. Rhizosphere competence, the relative root colonizing ability of a strain, can be quantified by measuring the population it establishes on a root especially when compared to, or challenged by, a known root colonizer. The rhizosphere is that narrow zone of soil subject to the influence of living roots, as manifested by the leakage or exudation of substances that promote or inhibit microbial activity. Improved detection and monitoring methodology should aid in recovery and enumeration of introduced bacteria. Although not entirely effective, the plate count method is still in the most commonly used method. Antibiotic resistance traits have also been used for purpose of monitoring. The development of reliable genetic markers and monitoring tools for detection is an evolving science requiring research. Root colonization by introduced bacteria is also influenced by host genotype type and bacterial traits such as surface polysaccharides, fimbriae, flagella, chemotaxis and osmotolerance, and ability to use carbohydrates.

COMMERCIAL DEVELOPMENT

For an agricultural product to be worthy of commercial development the following criteria must be met:

1. There must be a demand for the commercial product.
2. The market size should be large enough for satisfactory return within a reasonable time.
3. Broad spectrum activity is a pre-requisite for enhancing market size.
4. Performance must be high and reliable.
5. Product must be free from toxicological problems.
6. Good storage without special requirements.
7. The end user formulation must have a minimum shelf life of one year at room temperature.
8. Manufacture must be cost-effective.
9. The formulated product must be capable of being applied using standard machinery.
10. The microorganism must have rapid colonization potential and good persistence.
11. The product must be compatible with integrated control programs.
12. The product must be safe to use.

Niches for Microbials Given the limitations of microbial products compared to fungicides, it makes sense, at least in the beginning, to avoid markets where there are already effective chemicals available. However, niches for microbials may exist for the reasons given below.

1. There are no effective chemicals.
2. Pathogens becoming resistant to chemicals.
3. Use of chemicals are too expensive.
4. Use of chemicals is restricted by legislation, particularly in Canada there is a strong political pressure to ban synthetic chemical pesticides use in forests.
5. Horticulture industry has an added advantage because these crops are grown in controlled environments.

Integrated Use of Microbials Although it is well established that certain diseases can be controlled completely or partially by the use of biocontrol agents it is understood that the effective method to control diseases is through integrated pest management wherein the biological control component would be significant. Pest management practices could be used jointly with biocontrol agents, including the use of chemical pesticides at reduced levels, or with resistant cultivars, or with other cultural practices. This approach may prove more effective where no single component is effective in controlling a particular disease.

Programs for improving the effectiveness of microbials Genetic manipulation of biological control agents offers a possible approach to improving their potential for plant disease control. This approach has been very successful in industrial microbiology. Efforts have been made in this direction by the research workers involved in biological control of insect pests. It has been visualized that the next decade will see a wide exploitation of genetic engineering and biotechnology in the service of biological control. For example a mutation in *Trichoderma harzianum* Rifai caused by ultraviolet irradiation amplified its biocontrol potential against *Rhizoctonia* damping-off of cotton and radishes, white rot of onion caused by *S. cepivorum*, and damping-off of peas caused by *P. ultimum* (Chet 1987). The mutation also improved the tolerance of *T. harzianum* to chemicals.

CONCLUSION AND PROSPECTS

Current research with microbials has been very encouraging. Some research reports demonstrate the possibility of manipulating the rhizosphere microflora in favour of improved plant growth and disease control. Microbials can be used as effective and reliable biological control agents which offer commercially viable business opportunities. At present, these opportunities are restricted to markets which are smaller in relation to the chemical markets. This change in attitude is in part linked to the technological advances which now offer the opportunity for generating really effective and reliable products. Still, some of the constraints have to be worked out for successful commercial products and I expect this can be easily managed.

1. It is likely that specific bacterial strains are needed for particular diseases; it is always worth looking for new strains.
2. Changes are needed in cropping sequences and agricultural practices to enhance the efficacy of microbials.
3. Plant breeders and genetic engineers have to work together to design the host and antagonist to be compatible, and mutually harmful, to the pathogen.
4. The consistency of performance must be improved. Assurance that the products delivered to the users have a high level of potency and purity is needed, and should be guaranteed on the product labels.
5. Research has to be directed to identify important traits that help in root colonization and pathogen antagonism.
6. More research on formulation and delivery of the microbials is needed.
7. Increased efforts should be directed toward a better understanding of the mechanisms by which these microbials work.
8. In addition to exploring the host, soil, and environmental factors that can affect root colonization, superior screening methods must be developed.
9. When mechanisms by which the introduced microbial agents stimulate plant growth or control diseases are better understood, the likelihood of being able to select more effective strains and to improve the factors responsible for their establishment in the rhizosphere will be greatly increased.

The potential uses of microbials in world food production are great and will some day have a tremendous impact. It is premature now, however, to speculate on the many possibilities since this area of research is still in its infancy. Biological control, no doubt, can overcome various problems arising due to the use of pesticides and other poisonous substances. It will, for example, certainly reduce the pollution risk and in the future will free the farmer from the constant worry of disease destroying his livelihood.

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Weed Control with Mycoherbicides

R.S. Winder
Department of Plant Science, Macdonald College of McGill University, Ste Anne-de-Bellevue, Québec H9X 1C0

ABSTRACT *Mycoherbicides are indigenous fungal plant pathogens which control weeds through inundative applications. They can potentially replace, augment, or reduce the use of chemical herbicides. Mycoherbicide programs in Canada and other countries have produced several successes, but the paucity of "magic bullets" has made it necessary to achieve a clearer understanding of weed diseases. Environmental, physiological, and etiological factors all play a role in determining the virulence of a mycoherbicide. Currently, formulation, timing, and genetic manipulation are the main tools available for optimization of virulence and achievement of consistent field results. Overcoming biological, economical, and political constraints will hopefully result in better ways to control weeds.*

INTRODUCTION

Bioherbicides are biocontrol agents which are endemic and applied inundatively to control undesired vegetation. This is in contrast to the classical approach, which employs exotic species to establish a continuous epidemic suppression. The term "mycoherbicide" refers to bioherbicides which are fungal plant pathogens. Fungi are the most prevalent group of organisms being studied as potential bioherbicides, hence the frequent use of both terms. Phytotoxins and other fungal products are excluded from these definitions. A number of reviews document the methodologies and current status of bioherbicide research (Charudattan 1988, Hasan 1988, Scheepens and van Zon 1982, TeBeest and Templeton 1985, Templeton 1982a, 1982b, Templeton et al. 1979, Templeton et al. 1986, Watson 1989). This paper will outline the current status of bioherbicide research, with an emphasis on information applicable to Canadian programs.

FUNDAMENTAL PRINCIPLES

Safety is a principal concern in the bioherbicide approach. Although they are applied like chemicals, bioherbicides are living organisms for which most conventional biocontrol theory is relevant. Typically host-specific, their use is intended to be a low risk to human health and environmental integrity (deJong et al. 1990, Pimentel 1980). This is because bioherbicides are indigenous and/or endemic and designed to potentially replace, augment, or reduce usage of chemical herbicides. Replacement would occur if a bioherbicide can match or exceed the economy and effectiveness of a chemical herbicide (Charudattan et al. 1986). Augmentation would occur if the bioherbicide can control weeds which cannot be controlled by chemicals (Smith 1986). Reduction would occur when lower rates of a chemical are used due to additive or synergistic effects from a bioherbicide (Wymore and Watson 1989).

Efficacy or effectiveness is the other major concern in the bioherbicide approach. The principles of phytopathology are applicable to this topic. The three pillars of weed disease etiology are the host, the pathogen, and the environment — the "disease triangle" of plant pathology. To develop a bioherbicide, these factors must work to enhance the disease, rather than prevent it. As in plant protection efforts, this goal is often achieved with mixed success — wherein lies the challenge. There are complications to consider in the weed disease triangle. In terms of the host, for example, domesticated crop plants may be more susceptible to well known diseases than a typical weed with its "wild type" resistance to uninvestigated pathogens. In addition,

Table 1. Examples of bioherbicide research projects outside Canada.

Target weed	Pathogen	Location	Reference
Cassia obtusifolia	*Alternaria cassiae*	USA	Charudattan et al. 1986
Cucurbita texana	*Fusarium solani*	USA	Weidemann and Templeton 1988
Desmodium tortuosum	*Colletotrichum truncatum*	USA	Cardina et al. 1988
Echinochloa crusgalli	*Cochliobolus lunatus*	Netherlands	Scheepens 1987
Pteridium aquilinum	*Ascochyta pteridis*	UK	Burge et al. 1988
Sorghum halepense	*Bipolaris sorghicola*	USA	Winder and Van Dyke 1990
Xanthium spinosum	*Colletotrichum orbiculare*	Australia	Auld et al. 1988
Cyperus esculentus	*Puccinia canaliculata*	USA	Phatak et al. 1983

only certain parts or stages of the plant may be susceptible (Winder and van Dyke, 1990, Wymore et al. 1988). In terms of the pathogen, virulence may be difficult to maintain during inoculum production and storage (Reincke 1990, Zelikovitch and Eyal 1989). In terms of the environment, major fluctuations in temperature, humidity, precipitation, or dew period can inhibit disease development (Charudattan et al. 1986, Morin et al. 1989). Despite these limitations, epidemic weed diseases are commonly observed in situ.

MYCOHERBICIDES

There are no strict rules that determine what kind of fungus can become a mycoherbicide. Generally, mycoherbicides are derived from host-specific foliar pathogens, but there are exceptions (Templeton 1982b). Most mycoherbicides come from the higher fungi: the ascomycetes, the basidiomycetes, and the deuteromycetes (or imperfect fungi). The typical mycoherbicide is a facultative parasite which can grow saprobically on artificial media. However, some research is concentrating on mass production and deployment of obligate parasites such as rusts (Paul and Ayres 1987, Phatak et al. 1983). Although much work has concentrated on pathogens of broadleaf weeds, there have been some investigations of monocot pathogens (Winder and van Dyke 1990).

DEVELOPMENT

There are three steps in producing a marketable bioherbicide: discovery, development, and deployment. As a result of exploration and collection, candidate fungi can be discovered on diseased weeds or seeds. During this first phase, the pathogen must be grown on suitable media, isolated in pure form, proven to be pathogenic, and placed into storage.

The development phase addresses the primary concerns of safety and efficacy. Information on safety is gained through host-range testing and by elucidating the mechanism of action of the pathogen. Information on efficacy is gained by discovering when optimal disease development occurs in relation to environmental and physiological factors such as inoculum density, dew period, growth stage, temperature, etc. Adjuvants are formulated to mitigate the inhibitory effects of these factors, and disease etiology becomes a third important factor at this point. Adjuvants can have a profound impact on disease development, potentially affecting every aspect of disease from spore germination onward (see later sections of this paper). A third concern during the development phase is inoculum production. Efficient ways of generating large quantities of viable inoculum are important for field-testing and eventual commercialization. Large scale liquid cultures are often employed; the inoculum may consist of hyphae, conidia, chlamydospores, or other structures (Churchill 1982, Morin et al. 1989).

The deployment phase involves all research necessary to commercialize the bioherbicide: field-testing, continued formulation, scale-up of inoculum

Table 2. A list of bioherbicide research programs in Canada.

Institution	Focus	Target weeds	References
Agriculture Canada (Regina)	general/agronomic	*Malva pusilla* etc.	Mortensen 1988
Forestry Canada (Victoria)	sylvicultural	hardwoods etc.	Dorworth 1988; Wall (unpublished)
Macdonald College (McGill University)	agronomic/ sylvicultural/ urban	*Abutilon theophrasti*, *Epilobium angustifolium*, *Plantago major* etc.	Wymore and Watson 1989; Winder and Watson 1990; Tourigny et al. 1990
Université Laval	sylvicultural	*Rubus* spp.	Thibault (unpublished)
University of Guelph	general	(In discovery phase)	
Alberta Environmental Centre	general	(In discovery phase)	
Agriculture Canada (Harrow)	general	(In discovery phase)	
Nova Scotia Agricultural College	agronomic/ sylvicultural	(In discovery phase)	

production, and eventual test-marketing. Because this stage of research requires substantial resources, collaboration with the industrial sector is usually sought at this point. For several reasons, industrial collaborations have proven to be difficult. Although the costs of development may be low, the market share for a host-specific bioherbicide could also be low (Reincke 1990, Watson and Wymore 1990). In established markets, users might prefer to keep using chemicals as a kind of 'insurance policy'. Some potential bioherbicides do not perform as consistently as chemicals, a point which needs further study (Reincke 1990, Watson 1989). The deployment step is probably the most difficult aspect of bioherbicide development. Industrial collaboration in Canada has included such companies as Philom Bios, Elanco, and Rhône-Poulenc.

STATE OF THE ART

General status There are two registered commercial mycoherbicides. In 1981, a liquid formulation of *Phytophthora palmivora* called DeVine® was registered for control of stranglervine, *Morrenia odorata* (Hook. & Arn.) Lindl., in Florida citrus groves (Templeton 1982). In 1982, a dry powder formulation of *Colletotrichum gloeosporioides* (Penz.) Penz. and Sacc. f. sp. *aeschynomene* called Collego® was registered for control of northern jointvetch, *Aeschynomene virginica* (L.) B.S.P., in rice and soybeans in the southeastern USA. (Smith 1986). A sampling of bioherbicide programs in countries outside of Canada is shown in Table 1.

In Canada, there has been much progress in bioherbicide research. Several programs are outlined in Table 2.

Agronomic sector There are several potential mycoherbicides being developed for the Canadian agronomic sector. *Colletotrichum gloeosporioides* f. sp. *malvae* is a pathogen of round-leaved mallow, *Malva pusilla* Sm., in the deployment phase of research. Round-leaved mallow is a troublesome weed during moist conditions in places such as southern Manitoba. Beyond the early seedling stage, it is difficult to control with chemicals. The pathogen is capable of controlling the weed with 16–20 h of dew at 20–25°C. It also displays some activity against velvetleaf, *Abutilon theophrasti* Medic., another weed in the Malvaceae (Mortensen 1988). *Colletotrichum coccodes* (Wallr.) Hughes is another pathogen of velvetleaf in the deployment phase of research. Velvetleaf is a problem in corn and soybean fields in North America. Tolerant of many herbicides, it can be effectively controlled by a mixture of *C. coccodes* and thidiazuron, a plant growth regulator. Optimal activity of this bioherbicide requires 18 h of dew at 24°C (Wymore and Watson 1989, Wymore et al. 1988). Other bioherbicides are in the development phase for this sector. They include *Phomopsis convolvulus* Ormeno for control of field bindweed, *Convolvulus arvensis* L., (Morin et al. 1989) and *Ascochyta hyalospora* (Cooke and Ell.) Boerema, Mathur and Neergard for control of lambsquarters, *Chenopodium album* L. (Allan et al. 1987).

Forestry sector. As trees are a major Canadian resource, it is not surprising to find a number of mycoherbicide researchers focusing on the forestry sector. In this sector, mycoherbicides are primarily intended for use in reforestation areas where various weeds compete with young tree seedlings. A form species of *Colletotrichum dematium* (Pers.:Fr.) Grove is being developed to control fireweed, *Epilobium angustifolium* L., a major problem in some reforestation areas in Québec and British Columbia. This potential mycoherbicide requires a dew period greater than 18 hours (Winder and Watson 1990). Other major weeds which have been targeted in this sector include raspberry, *Rubus* spp., (Dorworth 1988, Thibault 1989), maple, *Acer* spp., (Dorworth 1988, Wall 1990), and wild cherry, *Prunus* spp. (Wall 1984).

Urban sector In the urban category, a *Colletotrichum* species is being studied in Canada for control of *Plantago major* L. in lawns (Tourigny et al. 1990). Dandelions, *Taraxacum officinale* Weber, and sow-thistles, *Sonchus* spp., are other obvious targets for mycoherbicides in this sector. Ragweed, *Ambrosia artemisiifolia* L., is an urban target in Montréal, where fines can be levied for letting it grow.

Other sectors Mycoherbicides could be sought for a variety of weed problems in Canada. Weeds of roadsides and drainage areas such as reeds, *Phragmites communis* (L.) Trin., may be susceptible to mycoherbicides. In sensitive conservation areas, biological control of invaders like purple loosestrife, *Lythrum salicaria* L., has been proposed (Thompson et al. 1987). There are many plants causing problems in grazing, utility, recreational, and right-of-way areas which could also be considered targets.

PROBLEMS AND PROGRESS

Biological factors It has become increasingly necessary to study the basic details of disease ontogeny in order to improve efficacy. For example, increasing inoculum densities may not necessarily result in greater damage if spore germination is inhibited at high concentrations (Lewis et al. 1988). The details of spore germination, formation of appressoria, and all of the subsequent events of infection can vary in each system.

Formulation is one tool we have to overcome the limitations inherent in pathosystem diversity. In the spore germination example, it is possible to remove inhibitory effects during formulation of inoculum (Winder and Watson 1990). Other types of formulations can remove dew-period requirements (Connick et al. 1989, Quimby and Fulgham 1986), stimulate germination (Winder and Van Dyke 1990), affect the cuticle, and otherwise improve virulence (Bannon 1988). As a compound formulation, bioherbicides can be tank-mixed with other herbicides to produce an additive or synergistic effect (Scheepens 1987, Wymore and Watson 1989). Because formulation can have such a profound impact on disease, pathogens causing light damage in initial trials need not be automatically ruled out as potential bioherbicides. A list of formulations appears in Table 3.

Timing is the second tool that can be used to counter biological limitations. Timing can mean application at susceptible stages (Winder and Van Dyke 1990,Wymore et al. 1988), application at the appropriate time of day (Winder and Van Dyke 1990,Wymore et al. 1988), application in appropriate weather (Mortensen 1988), or sequential application (Watson and Wymore 1990). Timing also applies to the pathogen, in terms of which stage produces the best inoculum and how long the fungus can be stored.

The possibility of using genetic engineering to overcome biological limitations is being explored as a third option (Greaves et al. 1989). In this scheme, genes involved in pathogenesis can be derepressed, copied, mutated, transferred, or otherwise improved to ensure virulence. Resistance to tank-mixing with other pesticides is another possible goal of this type of research. Such resistance is needed if bioherbicides are to be integrated with other weed control systems (Smith 1990, Smith 1986). The pathogenicity or host-range of a pathogen might also be altered using these techniques. Bioengineering adds an extra level of difficulty to registration efforts

Table 3. A list of adjuvants used or proposed for mycoherbicide formulations and their possible functions.

Adjuvant	Possible functions	Reference
simple sugars	modify spore rehydration	Smith 1986
surfactants and surfactant/oil mixtures	leaf-wetting	Bannon 1988
	growth stimulus	Winder and Van Dyke 1990
	humectant, cuticular penetration, modification of transport phenomena?	McWhorter 1987
lecithin/wax mix, glycerides, etc.	invert emulsion/humectant	Connick et al. 1989, Quimby and Fulgham 1986
	adhesion	Boyette and Quimby 1990
proteins	surrogate matrix/adhesion	Winder and Watson 1990
	humectant	Fravel et al. 1985
pectins/pectinase	host range expansion	Boyette 1987, Boyette et al. 1987
xanthan gum	adhesion/humectant?	Cardina and Litrell 1986
Salts, extracts, other compounds	growth stimulant	Stowell et al. 1987, Winder and Watson 1990
Chemical herbicides and growth regulators	Enhancement of susceptibility	Scheepens 1987, Winder and Van Dyke 1990, Wymore and Watson 1989
Other organisms	host range expansion	Watson and Wymore 1990
	modify susceptibility (often antagonistic)	Baker and Cook 1982

(Reincke 1990).

Other biological factors, including the possible emergence of resistant hosts, have been cited as possible limitations. It is important to realize, however, that Collego® is an example of a mycoherbicide which has been used very successfully for more than a decade with no such difficulties (Smith 1986).

Economic factors The development costs for Collego® were about $1.0 to $1.5 million U.S., compared to $25 to $50 million U.S. for a typical chemical. Despite these facts, mycoherbicides will probably be integrated into weed control programs very slowly if industrial collaboration continues to lag (Reincke 1990,Watson and Wymore 1990).

Political factors The political sector is charged with determining the safety of bioherbicides. On a basic level, this concern rests with specificity. Bioherbicides should be safe to humans, crops, and the environment. As most bioherbicides are indigenous and/or endemic, this has not been difficult to demonstrate in terms of pathogenicity (Scheepens and van Zon 1982, Smith 1986). Demonstrating the safety of phytotoxins, mycotoxins, and phytoalexins produced during the disease reaction may be problematic, however. Although the levels reaching the food chain are presumably very minute, no work has established quantitative examples. In Canada, guidelines for bioherbicide registration are still being developed. If it falls to small businesses and cottage industries to promote bioherbicide development, the role of the government in maintaining reasonable levels of regulation will become of paramount importance (Watson and Wymore 1990).

PROSPECTS

Some researchers view bioherbicides as a potential part of integrated pest management, and not as a complete alternative to chemicals (Watson 1989). The success of bioherbicides will probably depend on mutual cooperation between academia, industry, and consumers. Consumers have the right to demand a workable product, but they also have to be able to adapt. The notion of rapid and complete weed mortality as an ideal situation may have to be challenged (Paul and Ayres 1987, Watson 1989). Additionally, the usage of bioherbicides will entail some changes in equipment and procedures. Industry has the right to expect a profit from its endeavours, but it must also be ready to adapt. The benefits of basic research and the relative scarcity of "magic bullets" need to be recognized. In academia, researchers will have to balance their concerns between scientific discovery and economic reality (Watson 1989). The views of regulatory agencies must be taken into account by all sectors. If these conditions can be met, bioherbicides could have a chance to become important tools in weed management.

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Classical Biological Control of Weeds

P. Harris
Agriculture Canada, Research Station, PO Box 440, Regina, Saskatchewan S4P 3A2

ABSTRACT *In classical biological control of weeds parasites, predators or pathogens are introduced from another region to regulate the target weed on a continuing basis. A complete program costs about $4 million and requires 20 scientist-years. It involves (1) studies to justify using biocontrol (2) overseas surveys for natural enemies (3) studies to show that candidate biocontrol agents will not damage desirable plants (4) establishment of approved agents on the weed (5) studies to determine their impact, and distribution of effective agents. Successful projects in Canada include the reduction of the toxic pasture weed St. John's-wort to about 1% of its former density; the reduction of nodding thistle from stands of 20 plants per m^2 to a temporary pioneer of disturbed habitats; and the reduction of leafy spurge on coarse, dry open soils from 100% cover to 5% by a root-feeding beetle. Seed production of diffuse and spotted knapweed has been reduced to about the number needed for population maintenance, so one more abundant agent should achieve control.*

INTRODUCTION

This paper outlines the steps involved in classical weed biocontrol and its effects. In the last part of the paper I raise a number of issues about the future organisation of weed biocontrol in Canada that need to be addressed.

DEFINITION OF BIOCONTROL

Beware of the term biological control or biocontrol unless it is defined. The term was first employed by Smith (1919) for natural enemies (predators and parasitoids) used for the control of pest insects. The words have since acquired a motherhood image and are now used to promote a wide range of approaches to pest control. They are used for displacement planting (such as sowing crested wheat grass for control of range weeds), for grazing management, for crop rotation, for breeding pest resistant crop varieties, for the release of sterile male insects, and even for organically produced chemical pesticides (Neish 1988, Garcia et al. 1988, Gabriel and Cook 1990, Garcia et al. 1990). The picture is further confused as biocontrol is covered by legislation with its own terminology.

A particular definition cannot be enforced but at least everyone using the term should be able to define it. I like the definition of biocontrol used by Harley (1985): "the study and utilization of parasites, predators and pathogens to regulate the populations of pests". As far as I am concerned the biocontrol agents may be genetically modified, but they must attack the pest. I exclude domestic animals. In my opinion a relatively narrow definition is needed for discussion purposes. The alternative is to abandon the generic term and just use the terms classical and inundative biocontrol; however, Gabriel and Cook (1990) still argue for a broadly based meaning that encompasses all biologically based pest control methods.

Biocontrol as defined here divides into two approaches, inundative and classical, that are under different legislation in Canada and most other countries. Inundative biocontrol involves the application of an organism to the pest where and when it is a problem, in much the same manner as a chemical pesticide. It can be regulated on a continuing basis at the market place like a pesticide and comes under the Pest Control Products Act (Canada 1985b) as do pesticides, although they are under different regulations. Classical biocontrol of weeds involves the establishment of organisms from another region to give control on a continuing basis.

The only legislative control possible is at the time of release into the new region. The enabling legislation is the Plant Quarantine Act (Canada 1985a), which is designed to prevent the introduction and spreading of plant pests.

IMPACT AND WEED PROBLEMS SUITABLE FOR CLASSICAL BIOCONTROL

The effect of classical weed biocontrol is to selectively reduce the problem weed without harm to the associated plant species, which consequently increase. It can be the most economic and ecologically satisfactory method of solving certain weed problems. Its use and effects are illustrated by discussion of several projects.

St. John's-wort, *Hypericum perforatum* L. The introduced range weed St. John's-wort has been reduced to about 1% of its former density in much of southern British Columbia, Ontario, and the Maritimes by the defoliating beetles *Chrysolina quadrigemina* (Suffrian) and *C. hyperici* (Forester) (Harris and Maw 1984). The weed remains even in the preferred beetle habitats and there are several habitats where the beetle has done poorly in which the weed is still abundant (Williams 1984). The herbaceous vegetation on most of the former St. John's-wort sites is now an association with many codominants, although some sites have been recently overrun by spotted knapweed, another introduced weed. The biocontrol of one plant species provides no assurance that the habitat will not be dominated by another undesirable plant species. On the sites with abundant St. John's-wort we have established a defoliating moth, *Anaitis plagiata* (L.), a root-feeding beetle, *Agrilus hyperici* (Crotch) and have recently released an aphid, *Aphis chloris* (Koch), to add further pressure on the weed.

Nodding thistle, *Carduus nutans* L. The biocontrol of nodding thistle with the seed-head weevil *Rhinocyllus conicus* (Frölich) restricted this introduced plant to recently disturbed uncultivated sites (Harris 1984). Thus, it now occurs on rangeland in gopher diggings, openings where a stone has been moved or on pastures abused by overgrazing or drought. Formerly, once established, the thistle remained a dominant that prevented the return of grass and other herbaceous plants. Now pasture returns in about three years unless the area is redisturbed. The thistle is still common on railroad sides, gravel pits, and vacant lots in cities. These sites provide a sanctuary for the weevil from which it can move onto the rangeland when the thistle reappears. Normally a biocontrol agent works best if the weed is under competition from other vegetation. Thus *R. conicus* works better against nodding thistle on rangeland where there is grass competition than on a railroad side where the competition is low. It may be necessary to establish several insects on a single weed to achieve economic control as the individual species have different site requirements or each does not do enough damage by itself.

Leafy spurge, *Euphorbia esula* L. Leafy spurge is an introduced plant that tends to form a 100% cover on uncultivated land in the southern Canadian prairies. The target for biocontrol is to reduce its cover to 5% on at least 95% of the infestation.

We are having some success. The beetle *Aphthona nigriscutis* Foudras has reduced the weed to the 5% target at release sites on open dry coarse soils. Early results are given by Harris (1990). The beetle is not working in swales or in the shade. The best indicator that I have found of suitable sites for the beetle is the needle and thread grass, *Stipa comata* Trin. and Rupr. *A. nigriscutis* should solve the problem on about 40% of the Canadian spurge infestation.

The beetle *A. cyparissiae* Koch has a similar effect on spurge growing in slightly moister soils with the green needle grass, *S. viridula* Trin. Thus it is effective in swales, on sandy loam soils and in partial shade. *A. flava* Guillebeau is established on spurge stands near rivers and accepts shade, *A. czwalinae* Weise requires moist clay soils and *A. lacertosa* Rosenh. loam soils. We are gradually acquiring an arsenal of agents to attack spurge in its various habitats. Our main need now is for species that like shade. Clearly one of the costs and difficulties of this program is that the agents have much narrower ecological requirements than their host plant.

Other projects Successes have been achieved against tansy ragwort, *Senecio jacobaea* L., (Harris et al. 1984) and bull thistle, *Cirsium vulgare* (Savi) Ten. (Harris and Wilkinson 1984). Results are encouraging against diffuse and spotted knapweed, *Centaurea diffusa* Lam. and *C. maculosa* Lam., (Harris and Myers 1984) but as with leafy spurge we still need more agents. Screening of agents has been started for the biocontrol of scentless chamomile, *Matricaria perforata* Mérat, and hound's-tongue, *Cynoglossum officinale* L.

In total 22 weed species are targeted for classical weed biocontrol in Canada and 54 agents have been released against them. About a third of the agents have failed to establish, a third are established at low densities and so do little harm to the weed, and a third are numerous but do not necessarily control the weed by themselves (Harris 1986). A complete program against an introduced rangeland weed costs about 20 scientist years spread over 20 calendar years (Harris 1979). In present terms the cost is around $4 million.

All of the Canadian weed projects have been against dominant and abundant introduced weeds on uncultivated land. This is the traditional approach. However, Australia has had spectacular success with a rust disease against skeleton weed, *Chondrilla juncea* L., a dominant, abundant introduced weed on cultivated land. This project is worth $25 million a year, much of it to the wheat industry (Marsden et al. 1980). Also, in the USSR a Canadian beetle, *Zygogramma suturalis* (F.), which defoliates ragweed, *Ambrosia artemisiifolia* L., has increased crop yields in the infested region by 2–3 fold (Kovalev and Kechernin 1986). These examples show that classical biocontrol can be used against weeds of cultivated land, although the need to fit a biocontrol agent into the cultural practice reduces the available options. Both of the weeds were introduced, so there was a source of enemies with a narrow host range at the origin of the weed.

Several native North American weeds such as ragweed and, in Texas, snakeweeds, *Gutierrezia* spp., have close relatives in South America attacked by their own specialized insects. USDA investigations indicate some of them will accept the North American relative and not other plants (J. DeLoach, pers. comm. 1990). These examples challenge the traditional limits of classical weed biocontrol. The only common denominators remaining are that the weed is common, it is in competition with other plants and organisms exist that have a narrow host range.

STEPS IN A CLASSICAL WEED BIOCONTROL PROGRAM

There are five steps in classical weed biocontrol: 1. Studies to justify use of biological control against the weed. 2. Overseas surveys for natural enemies. 3. Screening of potential agents. 4. Establishment of approved agents on the weed. 5. Studies to determine the value of the agent.

1. Justification studies These studies quantify the weed problem, determine the agents already present on it, the extent to which interests benefiting from the weed, such as beekeeping, will be harmed, and the type of damage that is most harmful to the weed. For example, leafy spurge suffers relatively little from defoliation while St. John's-wort is severely affected. Thus, a defoliator such as *Chrysolina quadrigemina* is a good choice for the St. John's-wort but not for leafy spurge.

Justification for using biocontrol against a weed is a part of the environmental impact study required before an agent is approved for release. It is also irresponsible to spend $4 million of public money unless the project is in the public interest and there are reasonable prospects of success. The public interest aspect arises as the agent will not respect property lines so benefits of control have to be balanced against detriments.

The data on the losses from a weed must be obtained from the main areas affected and this means local involvement. Thus Alberta has been collecting data on the losses from yellow toadflax, *Linaria vulgaris* Mill., as it is the main province affected. The results of the studies are sometimes surprising. Peschken and Darwent (1985) collected data on the losses and benefits of narrow-leaved hawk's-beard in Saskatchewan. They found that contrary to general belief, the weed was not responsible for major losses, so its biocontrol could not be justified, although it was also not an important honey plant, as previously supposed.

2. Overseas Surveys Surveys of potential agents on a European weed are usually done under contract by the CAB International Institute of Biological Control, more commonly known as the CIBC. Agriculture Canada currently contributes about $300,000 a year towards the CIBC overhead on both weed and insect biocontrol projects. This is in addition to 2 scientist years ($400,000) on classical weed biocontrol at the Regina Research Station as well as another 2 scientist years on inundative weed biocontrol. The cost for a survey by the CIBC is likely to be around $40,000.

Often a sponsoring agency wants to dispense with a survey and get an agent released as soon as possible. An agent can be selected from the literature and others, possibly better ones, found in the course of working on the first. This is one of the realities of biocontrol (Waage 1990).

3. Host range testing of potential agents The purpose of the testing is to show that the organism has a predictable host range that does not include desirable plant species. Essentially the agent must starve to death on the desirable plants in order to be acceptable or it must be shown in other ways that it is unlikely to do harm. The screening studies are submitted to Ottawa and Washington and the agent is either approved for release, rejected or further studies are required. The cost of screening an agent is about 2 scientist years ($400,000) and it is preferable to have it done overseas by the CIBC as the cost is about a third less than doing the work in quarantine in Canada and there is no danger of accidental escapes.

Most of the funds for the screening tests come from outside Agriculture Canada. For example, the 1990 budget for the overseas work on leafy spurge, excluding the overhead contributions by Agriculture Canada, is as follows: Saskatchewan $50,000; National Defence Canada $50,000; Agriculture Canada $12,011; Alberta $10,000; Ontario $10,000; village of Saskatchewan Beach $700 and (in US funds): Montana State $45,000; Montana Weed Districts $15,000; USDA-APHIS $15,000; North Dakota $10,000; South Dakota $10,000. At this level of spending all the agents necessary should be screened by 1994.

4. Establishment of approved agents Agents are usually difficult and expensive to obtain, as the weed is normally scarce at its source of origin. For example, the knapweed root-crown weevil, *Cyphocleonus achates* (Fahraeus), was established at Castlegar, BC, with a release of 25 individuals at a cost of $1,500 each. The agents are presumably partly responsible for the scarcity of the weed; but the situation is not helped by agricultural subsidies which have resulted in the cultivation of many areas in the native range that previously had knapweed.

The agents imported are often poorly adapted to the climate of the release site. For example, the *Chrysolina quadrigemina* beetle that has been successful against St. John's-wort did poorly for the first 5-13 years (Harris et al. 1969). The reason is that they stayed on the top of the plant as the temperatures dropped in the fall and got killed by early frosts. They now tend to seek shelter in the soil litter as the temperature drops and re-emerge to feed and oviposit when it rises again (Peschken 1972). This need for climatic adaptation is one of the reasons why biocontrol requires a period of 20 calendar years even if unlimited scientific resources are available. The period of acclimation is reduced if the collection and release areas are climatically matched; but this is not always possible. Given time it is often possible that a agent will thrive in regions where it failed or did poorly initially. For example, *Sphenoptera jugoslavica* Obenb. is a scarce diffuse knapweed root-feeding beetle that occurs in Europe at latitudes considerably south of the Canadian border. It was established at White Lake, BC with 188 beetles from Greece released in 1976. It initially did poorly but it is now widely established in the summer dry region along Highway No. 3 and as far north as Kamloops, and many thousands a year are being provided to the USA for release. Similarly, although stock of the St. John's-wort root-feeding beetle *Agrilus hyperici* from California were released a number of times in British Columbia, they failed to become established. Stock, originally from the Californian colony, has over a period of time been established further north in the USA. Establishment in British Columbia was finally achieved with stock imported from Lewiston, Idaho in 1987.

The objective of the initial release is to get at least one flourishing colony. If this is achieved, it is distributed to other regions with the weed problem. The regional colonies are then used for local distribution centres for public release on their own property. At this stage we also try to provide information leaflets so that the public can help themselves on a continuing basis.

5. Impact Studies An essential part of a classical weed biocontrol program is feedback on how the agent is doing. If one agent is not doing enough damage to achieve the objective, it is possible to increase the level of damage by adding other specialists. For example, the knapweed seed-head fly *Urophora quadrifasciata* Meigen adds to the seed destruction achieved by the fly *U. affinis* Frauenfeld (Myers and Harris 1980). On spotted knapweed each seed-head fly destroys an average of 8 seeds and in the Castlegar BC region they attack about 75% of the heads (Story et al. submitted). The root beetle *S. jugoslavica* on diffuse knapweed adds a further 20% to the seed destruction achieved by the two seed-head flies. As a result seed production has decreased from around 25,000 per m^2 in 1977 to 108 per m^2 in 1988. According to Powell and Myers (1988) current production is at or slightly below the maintenance level required by the weed. Thus, the addition of one more agent that becomes abundant on the weed should achieve a major reduction. However, extermination of the knapweed will not occur since the agents become decreasingly effective as weed density declines.

The results of weed biocontrol are summarised annually and distributed to the Provincial representatives to be used for planning their own programs.

FUTURE NEEDS AND ORGANIZATION OF WEED BIOCONTROL IN CANADA

Federal-provincial collaboration There have been many changes in classical weed biocontrol since I started. The work used to be funded and done by Agriculture Canada except for some help in making releases and sampling. It is now a joint federal-provincial effort and in my opinion there is no point in starting a program without the support of one or more provinces. I do not regret this as the work goes far better when there is local interest and participation. There is however a danger. At times of tight money, programs at both the federal and provincial level are greatly influenced by its popular appeal. The provincial distribution of the agents is highly visible and unless the federal and other contributions are recognized, I fear that funds will decline from these sources.

I would like to see federal and provincial weed biocontrol workers in Canada jointly determine priorities. So far the leadership for suggesting and planning projects as well as assembling a supporting consortium has been largely federal. This was perhaps necessary until provinces designated people to be responsible for weed biocontrol; but the program would be stronger with more regional participation and more interchange between provinces.

User groups The interest and support of a user group is of major benefit to a weed biocontrol program. The BC Cattlemen's Association have been vital to progress made against knapweed. User interest is the oil that keeps the wheels of government bureaucracy turning; but the user association is also a means of information transfer to their members. The public does not appreciate that the biocontrol of a weed is a 20 year program. Unless they understand, they lose interest before the objective is achieved. This is a waste as half a biocontrol project is no better than none. Most projects such as that against leafy spurge on the Prairies have considerable public support, but are not supported by a user association. Saskatchewan uses field days to explain the program. Nevertheless, I still get phone calls in early May asking why the spurge is still coming up and there are no beetles. The beetles do not emerge until late June and the normal result after one year is a depression of spurge in a 2 m radius. Classical weed biocontrol is a new and strange technology to most people and it will not be fully effective without public education.

Justification Justification data is becoming an obstacle to the start of new weed biocontrol projects. The data required has increased with the public interest in ecology. In cases where the public perception is that the weed is pretty or desirable, it may be politically essential to publish the justification study in a glossy form. This was done for purple loosestrife, *Lythrum salicaria* L., (Thompson et al. 1987) and it has changed public opinion from being generally antagonistic to supportive. With weeds such as leafy spurge, it is merely necessary to have a report available for anyone who wants to see it.

I strongly favour that approval to target a weed for biocontrol is treated separately from approval to release an agent on it, as is done under the Australian Biological Control Act (Australia 1984). In North America regulations require that the two reports are submitted together. It has happened that the weed is not approved so the agent screening was a waste. I am sure the requirement can be changed if there is group support for this. Apart from the approval aspect poor justification data has resulted in intermittent starting and stopping of a project, as has happened with toadflax.

Funding Funding for weed biocontrol from government sources is difficult and this is partly because much of it has to be spent overseas and hence does not immediately increase local employment. Montana has largely solved this problem by using a tax on chemical pesticides and road vehicles. Also, in Montana a company called BCW (for biological control of weeds) will provide agents and information to users for a fee. I think this will start and should be encouraged in Canada and I see no reason that they should not pay a royalty that goes back into biocontrol. This needs to be covered by a federal-provincial agreement as public funds from both sources have gone into the agent.

Legislation All Federal pest control legislation is under review. The new enabling legislation will determine what can and cannot be done and how smoothly approval can be obtained. Thus, it is important that people and organizations interested in biological control review the proposals and comment if they are not satisfactory. I would like to see Canada have a Biological Control Act similar to that in Australia rather than use the Quarantine Act, which is designed to keep plant pests out rather than to permit the release of beneficial species.

Forum Every discipline needs a forum and weed biocontrol is in the happy situation of being courted by several organisations. The Expert Committee on Weeds (ECW) is now eager to include weed biocontrol. They have a weed biocontrol subcommittee with a representative from each Province but have unfortunately stipulated that it will not meet. This makes it difficult to use ECW for discussion. I also doubt if they will lobby on our behalf for suitable legislation. They do however provide a good vehicle for informal publication of progress. Classical biocontrol, in contrast to inundative biocontrol, needs a different reporting format from that used for herbicides. I favour publishing an annual summary rather than individual reports on the species released in each province.

There is a biocontrol newsletter produced by the Biosystematics Research Institute in Ottawa that would like to publish annual contributions. Is this a better or poorer alternative or should we report in both?

All the biocontrol liberations in Canada are published annually by Agriculture Canada in "Insect Liberations in Canada". I would like to see its scope expanded to cover the decisions of the review committee on authorizations and any restrictions regarding agents approved for release, a summary of screening reports, and if we reach the stage of signing Federal-Provincial memoranda of agreements, these should be summarized and published. Perhaps this publication should be used for the annual summary.

There is need for a meeting forum and an organisation capable of presenting our views to government. The Entomological Society of Canada is independent of government and undertakes studies for presentation to government. At least half the weed biocontrol workers are entomologists, so it would be convenient to use the annual Entomological Society meeting as a forum.

Rearing facilities It is difficult to increase a biocontrol agent at Regina unless the weed occurs locally. Thus, there is a need for rearing facilities for new biocontrol agents in various parts of the country. These do not have to be run by government. For example, British Columbia and New Brunswick have contracted with the company Applied Bionomics to increase the tansy ragwort moth *Cochylis atricapitana* (Stephens) over winter so they will have several thousand for release next summer. British Columbia and Alberta also run their own rearing programs. A private company cannot be used unless one exists in a suitable region and they will not materialize unless a steady program of contracts can be provided. Possibly such companies could also be used for agent distribution as discussed under item 3.

In conclusion I suggest that classical biocontrol can achieve exciting results, there is widespread public support for it but if it is to be fully effective there are a number of problems to be solved. Many of these are organizational; however, desirable changes often do not occur unless they are requested.

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Biological Control of Aquatic Vegetation

J.T. O'Donovan

Alberta Environmental Centre, Bag 4000, Vegreville, Alberta T0B 4L0

ABSTRACT *Overabundant growth of aquatic vegetation interferes with irrigation, recreation, and water quality in water bodies throughout Canada. At present, aquatic weeds are managed mainly with herbicides, few of which are available for aquatic use, and mechanical methods, which can be laborious and expensive. Interest in biological control has therefore increased considerably. In Canada, research in this field has been limited. In a study in southern Alberta, the grass carp,* Ctenopharyngodon idella, *is proving effective in controlling problem aquatic vegetation in farm dugouts and irrigation canals. In British Columbia and Ontario, several insects have been found grazing on Eurasian watermilfoil,* Myriophyllum spicatum. *The most promising is the larva of the chironomid* Cricotopus myriophylli, *which feeds on the apical meristem, preventing flowering and emergence above the water surface. There seems to be no research in Canada on control of aquatic weeds with pathogens. In the USA, however, a promising fungus,* Mycoleptodiscus terrestris, *has been identified for control of Eurasian watermilfoil.*

INTRODUCTION

The overabundant growth of aquatic vegetation is a significant problem in Canada; weeds interfere with water flow in irrigation canals, recreational activities in lakes and rivers, and water quality in dugouts and other water bodies. Most of the problems are caused by submergent species. For example, in southern Alberta, submergent aquatic macrophytes such as sago pondweed, *Potamogeton pectinatus* L., Richardson's pondweed, *P. richardsonii* (Benn) Rydb., giant pondweed, *P. vaginatus* Turez, and alisma, *Alisma gramineum* Lej., have become overgrown in approximately 8,000 miles of irrigation canals (Allan 1983). Their presence can cause inadequate water flow for efficient irrigation, clogging of sprinkler valves, and flooding of farmlands. In addition to pondweed species, other aquatic macrophytes, including northern milfoil, *Myriophyllum exalbescens* Fern., coontail, *Ceratophyllum demersum* L., and Canadian pondweed, *Elodea canadensis* Michx., are also present in numerous recreational lakes and rivers throughout Canada, where they interfere with boating, fishing and swimming. Most of these species are native to North America.

Eurasian watermilfoil, *Myriophyllum spicatum* L., a species introduced to North America from Eurasia in the early 1800's, is very aggressive, and has the potential to become the most serious aquatic weed in Canada. It is not ubiquitous, but is a very serious problem in the Okanagan lakes of British Columbia and in parts of Ontario and Quebec. If left uncontrolled, it can spread very rapidly.

At present, the control of aquatic macrophytes in Canada is accomplished mainly with herbicides and mechanical harvesters. Irrigation districts depend almost exclusively on acrolein, the only herbicide registered for weed control while canals are operational. It is extremely toxic to fish (most are killed at less than 1 mg L^{-1}, while the rate of application is at least 2.5 mg L^{-1}). It provides only temporary control of weeds, and under some environmental conditions is only marginally effective. This method is costly, since continuous maintenance and frequent applications are required. The possibility of cheaper, environmentally safer herbicides being available in the future is slight, because the relatively small market, and the environmental sensitivity of aquatic systems, has made the chemical industry reluctant to develop new compounds. In the last fourteen years, only two aquatic herbicides, glyphosate and fluridone, have been registered in the USA. None have been registered in Canada during this period.

Mechanical control can offer a viable alternative to herbicides in some situations, but can be expensive, time consuming and laborious. Aquatic systems may need individually adapted machinery, and there can be detrimental effects on aquatic organisms. For example, Haller et al. (1980) estimated that mechanical removal of hydrilla, *Hydrilla verticillata* (L.F.) Royle, caused a fish mortality of 32%.

For these reasons, interest in the biological control of aquatic weeds has increased considerably in recent years. Control agents such as herbivorous fish, invertebrates, and pathogens have been used, with varying degrees of success, to combat aquatic macrophytes in various parts of the world. In Canada, control of aquatic weeds with biological agents has never been implemented on a large scale, and research on this subject has been very limited. This presentation reviews the use of these control agents, and discusses their potential for weed control in Canada. Recent research on biological control of aquatic weeds in Canada is highlighted.

REVIEW OF CONTROL AGENTS

Herbivorous fish The most widely used and most controversial biological control agent for aquatic weeds has been the grass carp, *Ctenopharyngodon idella* Valenciennes. This fish is a cyprinid, as is the common carp, *Cyprinus carpio* Martyshev, which was introduced into the USA and Canada in the 1800's. Although common carp became a nuisance from a fisheries management standpoint in some areas, no such problems have been reported for the grass carp.

The grass carp has been introduced into a number of countries including the UK (Fowler 1985), Holland (van Zon 1977), Egypt (Khattab and El-Gharably 1986), and parts of the USA (Sutton 1977, Henderson 1981, Pierce 1983), where it has successfully and economically controlled a variety of problem aquatic macrophytes in canals, lakes, ponds, and rivers. However, its use on a commercial basis is banned in many states of the USA, and in Canada.

The main concerns associated with the introduction of the grass carp are that it might reproduce, overpopulate, adversely affect aquatic ecosystems, and have a negative impact on sportfish productivity. The species, a native of the Amur River region which borders Heilongjiang (formerly Manchuria) and the USSR, requires very specific environmental conditions to spawn. Reproduction outside its native habitat is, therefore, unlikely; spawning has not been found to occur in the UK or western Europe (Fowler 1985). It has been documented in the lower Mississippi River system in the USA (Connor et al. 1980), but it is not clear whether the larvae survived to adulthood. Siltation and predation are considered major factors limiting larval survival.

The results of numerous studies conducted to determine the effects of the grass carp on aquatic ecosystems have been variable (Shireman and Smith 1983). In laboratory studies, the effects were either minimal, detrimental, or beneficial depending on factors such as stocking rate, macrophyte abundance, and structure of the ecosystem. Some variability has also been noted in field trials (Pierce 1983). In a five year study of 31 lakes in Arkansas, overall fish populations showed a downward trend in six lakes, an upward trend in eight lakes, and no significant change in 17 lakes. These studies suggest that there are no clear-cut effects of the grass carp on aquatic ecosystems. Pierce (1983) concluded that since its introduction into public waters in Arkansas in 1970, there have been no adverse effects on native fish populations. As well as maintaining aquatic vegetation at tolerable levels, the grass carp has become part of a thriving state fishery. Similarly, UK studies have confirmed that the species is highly unlikely to affect freshwater environments more seriously than mechanical or chemical methods which are now employed routinely (Moore 1983).

The grass carp is a voracious non-selective consumer of aquatic vegetation. Temperature has a major influence on feeding. Grass carp do not feed at water temperatures below 10°C; consumption increases as water temperatures increase above 13°C (Pierce, 1983). At 20°C, they may consume 50% of their body weight per day, and this may increase to 100% at 22°C (Opuszynski 1972).

There has been a concerted effort to develop a sterile form of the grass carp to eliminate any possibility of spawning in areas of introduction. Hybrids have been produced by fertilizing eggs of the female grass carp with sperm from the bighead carp, *Aristichthys nobilis* Rich. (Marian and Krasznai 1978). The F_1 hybrid is a sterile triploid with a somatic chromosome number of $2n = 72$, compared to $2n = 48$ for each parent. However, subsequent studies indicated slower growth, lower feeding rates, and higher mortality of hybrids compared to parents (Osborne 1982; Wattendorf and Shafland 1983;

Opuszynski et al. 1985). Their inadequate consumption of aquatic vegetation limits the use of the hybrids as biological control agents.

More recent technology resulted in the production of unhybridized triploid grass carp. Triploidy was induced by subjecting the fertilized eggs to either thermal shocks (Cassani and Caton 1985, Thompson et al. 1987) or hydrostatic pressure (Cassani and Caton 1986). The pressure shock method was most effective, consistently producing greater than 98% triploidy, and relatively high fish survival. Triploids appear to have the same voracious appetite for aquatic vegetation as the diploids (Wattendorf and Anderson 1984, Sutton 1985).

The inability of either the thermal or pressure shock methods to produce 100% triploid fish necessitates the use of a technique for differentiating between diploids and triploids. Some morphological differences exist between them, but these can only be determined with an accuracy of 65 - 85% (Bonar et al. 1988). A technique utilizing a Coulter counter and channelyzer provides a rapid, efficient method of determining ploidy in grass carp (Wattendorf 1986). This instrument can measure erythrocyte nuclear volume; since the nuclei of the triploid fish are larger than those of the diploid (due to the greater number of chromosomes), the method can be used to differentiate between them with virtually 100% accuracy.

In Canada, the first licensed introduction of sterile triploid grass carp for research purposes occurred in 1988. A multidisciplinary Committee on Biological Control of Aquatic Vegetation was formed in Alberta. It consists of members of various Alberta Government departments, Agriculture Canada, and the Alberta Irrigation Projects Association. The Committee embarked on a five year project to assess the feasibility of using the grass carp for control of aquatic vegetation in the irrigation canals in southern Alberta. The fish have been reared successfully under quarantine conditions at the Alberta Environmental Centre in Vegreville; they were determined to be 98% triploid (diploid fish were discarded) using the coulter counter method, and were deemed free of diseases that may be detrimental to native fish populations.

Studies on the effectiveness of the grass carp in controlling aquatic vegetation in dugouts and irrigation canals in southern Alberta, and their effects on water quality and other aspects of the aquatic environment, were initiated in 1989 under strict quarantine conditions. In keeping with the overall precautionary approach to this project, a section of irrigation canal in the Raymond Irrigation District opening into a landlocked lake was selected for the study, thus minimizing the chance of fish escaping into open water systems. Preliminary results indicate that the grass carp can effectively control nuisance aquatic vegetation in southern Alberta (D. Lloyd, Chairman, Committee on Biological Control of Aquatic Vegetation, personal communication). A major thrust over the remaining period of the project will be to develop appropriate fish stocking models for the irrigation canals.

A tropical herbivorous fish of the genus *Tilapia* has been used successfully for weed control in small water bodies in the USA (Schwartz et al. 1986). An advantage of these fish over the grass carp is that they do not survive water temperatures below 10°C, thus precluding any possibility of them overpopulating in Canadian waters. A research project is currently under way in southern Saskatchewan to investigate the use of *Tilapia* sp. for weed control in storm water retention ponds and farm dugouts (H. Peterson, Saskatchewan Research Council, personal communication). Aspects of the project include determining the optimum number and size of the fish when stocking, and how to harvest them in fall.

Insects The most notable successes in biological control of emergent or floating aquatic weeds have been achieved with insects. In appropriate situations, this type of biological control is by far the most cost-effective, since once established, it provides permanent control with no need for recurring treatments.

The earliest substantial success in biological control of an aquatic weed was achieved against alligatorweed, *Alternanthera philoxeroides* (Martius) Grisebach, a perennial native to South America, and a serious problem in many tropical areas. Two insect species, the flea-beetle *Agasicles hygrophila* Selman & Vogt, and the moth *Vogtia malloi* Pastrana (Maddox et al. 1971), were introduced into many areas and effectively controlled alligatorweed. The insects are now well established throughout the weed's US range, and other control methods are generally unnecessary (Julien 1987).

Water hyacinth, *Eichhornia crassipes* (Martius) Solms, is also native to South America, is widespread, and a serious problem in warmer regions of the world. Surveys of its native habitat identified several possible biological control agents, the most successful being the weevil *Neochetina eichhorniae* Hustache. The introduction of the insect provided substantial control of water hyacinth in the USA (Julien 1987).

The most spectacular success has been achieved against another floating weed, the water fern, *Salvinia molesta* Mitchell (Thomas and Room 1986). This plant can form floating mats up to 1 m thick and can double in size in only 2.2 days. In a region of Papua New Guinea, it threatened the livelihood of 80,000 people. Surveys for natural enemies in its native range (northern South America) found that the weevil *Cyrtobagous salviniae* Calder and Sands could effectively control the weed. When introduced to Papua New Guinea in 1982, it destroyed two million tonnes of the weed within two years (Thomas and Room 1986).

Control of submergent aquatic species with insects has not been as successful. Hydrilla, *Hydrilla verticillata* (L.F.) Royle, was introduced into the USA about 30 years ago, and is now considered the most serious aquatic weed. Weevils (*Bagous* sp.), leaf mining and stem boring flies (*Hydrellia* sp.), and aquatic moths (*Parapoynx* sp.) have been introduced into the USA and are being investigated as potential biological control agents for *Hydrilla* (Balciunas 1985). Two species, *Bagous affinis* and *B. laevigatus*, discovered in India and Pakistan, attack tubers of hydrilla (O'Brien and Pajni 1989), indicating that they may be successful control agents for this species.

Little research has been conducted in Canada on biological control of aquatic weeds with insects. There have been reports of insects grazing on Eurasian watermilfoil. One study suggested that grazing by aquatic larvae of the moth *Acentria* sp. was responsible for the rapid disappearance of Eurasian watermilfoil from three of the Kawartha lakes in Ontario (Painter and McCabe 1988).

Several insect species feed on Eurasian watermilfoil in the Okanagan lakes in British Columbia (Kangasniemi 1983; Kangasniemi and Oliver 1983). These include a caddisfly *Triaenodes tarda* Milne, weevils *Eubrychiopsis* sp., *Phytobius griseomicans* Schwartz (cited as *Litodactylus griseomicans* by Kangasniemi 1983) and *Parenthis vestitus* Dietz, and a chironomid *Cricotopus* sp., later named *Cricotopus myriophylli* Oliver (Oliver 1984). The chironomid appears the most likely candidate for biological control of Eurasian water milfoil. Failure of established beds of the weed to surface and flower in the Okanagan lakes system resulted from feeding damage by larvae of the chironomid, which feed in the apical region retarding or preventing flower development (Kangasniemi and Oliver 1983). Subsequent studies showed that one larva can crop one meristem of Eurasian watermilfoil, suppressing growth within one week of its introduction (Macrae et al. 1990). The larvae appear to be very host specific to *Myriophyllum* species. A project is currently under way to develop techniques for achieving mating and egg collection under laboratory conditions (P. Newroth, Water Management Branch, BC Ministry of the Environment, pers. comm.). If successful, it will result in the production of larvae for dissemination to areas where conditions for natural establishment of the insect may be suboptimal.

Little is known about insects that feed on *Potamogeton* spp. and other aquatic weeds native to Canada or North America. A study conducted in southern France found that the aquatic beetle *Haemonia appendiculata* Panzer can considerably reduce the abundance of sago pondweed, as well as Eurasian watermilfoil (Grillas 1988). The larvae bore into the stems close to the ground causing them to break. Several other aquatic plants, including *P. pusillus* L., a close relative of sago pondweed, were unaffected by the insect.

The genus *Haemonia* has not been recorded in the USA (Arnett 1968), and is therefore unlikely to occur in Canada. If introduced, it, or related species, may be likely candidates for biological control of Eurasian watermilfoil and sago pondweed. It is also possible that other consumers of *Potamogeton spp.*, and other problem aquatic weed species, may be present in Europe or Asia. However, it should be remembered that once an insect biological control agent is introduced, it is not possible to keep it confined to a restricted water body. If successfully established, it may spread to any adjacent regions where the host plant is available. Target weed species may play an important role in the ecology of some of these water bodies, for example, by providing food for waterfowl. The importance of the target weed species in aquatic ecosystems should, therefore, be evaluated carefully before the introduction of insects for biological control of aquatic weeds.

Pathogens As far as could be ascertained, no research on pathogenic control of aquatic weeds is being conducted in Canada. There has, however, been some research conducted in the USA. Most pathogens showing promise for biological control of aquatic weeds have been fungi. The most promising has been *Cercospora rodmanii* Conway, which causes considerable damage in the emergent species water hyacinth (Conway 1976; Conway and Freeman 1976).

It has been most effective when combined with another fungus *Acremonium zonatum* (Saw.) W. Gams, or with insects like the noctuid moth *Arzama densa* Walker, and the weevil *Neochetina eichhorniae* Warner. *C. rodmanii* has undergone extensive field testing and is awaiting commercial development (Charudattan et al. 1989).

Fungi that attack submergent species have also been identified. *Pythium carolinianum* Matt. may have potential as a biological control agent for parrotfeather, *Myriophyllum brasiliense* Camb., a species related to Eurasian watermilfoil (Bernhardt and Duniway 1984). It was isolated from several *Potamogeton* spp. including sago pondweed, but its potential as a control agent for these species was not determined. Several fungi have shown promise for control of Eurasian watermilfoil. These include *Fusarium sporotrichoides* Sherb., *Acremonium curvulum* W. Gams, and *Colletotrichum gloeosporioides* (Penz.) Sacc. (Andrews and Hecht 1981, Andrews et al. 1982, Smith et al. 1989a, 1989b). However, it was concluded that the poor ability of these fungi to penetrate the plant under field conditions may limit their usefulness as biological control agents. Another study showed that *C. gloeosporioides* enhanced the impact of a low rate of the herbicide endothall (Sorsa et al. 1988). This suggests that pathogens which are marginally effective when applied alone may have some promise in an integrated control system.

The most promising fungal pathogen isolated so far for biological control of Eurasian watermilfoil is *Mycoleptodiscus terrestris* (Gerdemann) Ostazeski (Gunner et al. 1990). Field applications of the fungus resulted in the virtual elimination of Eurasian watermilfoil from a treated plot within 10 weeks. Control was even greater when the fungus was applied in combination with a bacterium *Bacillus* sp. strain P8. These organisms are naturally resident in the phyllosphere of the plant, where they grow compatibly with each other, and are able to resist the inhibitory action of phenolic compounds produced by the plant. Specificity trials indicated that *M. terrestris* was only weakly pathogenic to other aquatic vegetation and terrestrial plants, suggesting little significant impact on non-target species.

The search for diseases of submergent weeds has focused mainly on those which attack foliage. In one study, however, asexual propagules of curlyleaf pondweed, *P. crispus* L., were frequently rotted when collected from drained irrigation canals in California (Bernhardt and Duniway 1986). Three of the fungi isolated from the propagules, *Fusarium crookwellense* Burgess, Nelson and Toussoun, *Papulaspora aspera* Bern. and Dun., and *Geotrichum* sp., colonized healthy propagules of pondweeds and healthy tubers of *Hydrilla* sp. when inoculated under laboratory conditions. Under field conditions, curlyleaf pondweed propagules inoculated with debris from any of the three fungal species were significantly more decayed than non-inoculated propagules.

Some of these fungi may have potential for control of Eurasian watermilfoil, pondweed species and other problem aquatic macrophytes in Canada. *M. terrestris* looks particularly promising as a control agent for Eurasian watermilfoil in areas where it is a major problem, such as the Okanagan lakes of British Columbia and the Kawartha lakes of Ontario. Fungi that attack asexual propagules may also be worth investigating as control agents. Tuber production is very important in the life cycle of sago pondweed, as well as being a major mechanism enabling the plant to escape incidental control measures such as the application of acrolein in irrigation canals. The herbicide does not affect the tubers which survive in the sediment and renew vegetative growth. It is also possible that some of these fungi are already associated with aquatic macrophytes in irrigation canals and other water bodies in Canada. Others with potential for biological control may also exist. A search for pathogenic agents does not appear to have been conducted in Canada. Such a study would be well worthwhile and may result in an effective tool for aquatic plant management.

SUMMARY AND CONCLUSIONS

In Canada, at present, effective, economical, and environmentally safe methods of aquatic vegetation management are not in general use. In the USA and elsewhere, biological control agents, including herbivorous fish, insects and pathogens, have been used with success. A limited amount of research on biological control agents for aquatic weeds is under way in Canada. A study in Alberta is investigating the feasibility of using the grass carp for control of aquatic weeds in irrigation canals. The project is in its third year, and so far the results are very encouraging. The fish have been confirmed as triploid and sterile, and have been shown to be free of any diseases that may be detrimental to native fish.

It is proving very effective in controlling problem aquatic vegetation in farm dugouts and irrigation canals in southern Alberta. A major focus over the remaining time of the project will be to develop appropriate fish stocking models for the canals.

The limited research in Canada on control of aquatic weeds with insects has focused on Eurasian watermilfoil. In British Columbia and Ontario, several insects graze on the weed. The most promising is the larva of the chironomid *Cricotopus myriophylli*, which feeds on the apical meristem, preventing flowering and emergence above the water surface. A study currently under way in British Columbia should determine if mass rearing of the insect is feasible.

As far as could be determined, no research is being conducted in Canada on control of aquatic weeds with pathogens. From work conducted elsewhere, the most promising fungal candidate for control of Eurasian watermilfoil is *Mycoleptodiscus terrestris*, especially when used in combination with *Bacillus* sp. This could prove to be a major control agent for Eurasian watermilfoil, but needs to be tested under Canadian conditions. Native aquatic macrophytes may also harbour fungal and bacterial agents, which if applied in sufficient concentration may be effective control agents. A survey of aquatic vegetation in Canada for pathogenic agents would be well worth the undertaking.

Effective aquatic plant management for specific situations in Canada may require more than one biological control agent. For example, in areas where Eurasian watermilfoil is very abundant, combinations of *C. myriophylli*, *M. terrestris*, and *Bacillus* sp. may be effective, and should be investigated under Canadian conditions. Other situations may require a more integrated approach to the problem involving one or more biological control agents, as well as chemical and/or mechanical methods. For example, the use of pathogens in combination with low herbicide rates warrants further study.

Finally, while the projects currently under way in Canada are major steps in the right direction, there is room for considerably more research on biological control of aquatic weeds if our most important natural resource is to be kept free of unwanted vegetation by environmentally safe, economical, and effective methods.

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Biological Control of Livestock Pests

T.J. Lysyk
Agriculture Canada, Research Station, PO Box 3000, Lethbridge, Alberta T1J 4B1

ABSTRACT *Biological control of livestock pests in the family Muscidae is described. The life histories of the horn fly, the stable fly, the house fly and the face fly are reviewed in relation to livestock production systems and biological control potential. Use of parasitoids in the family Pteromalidae has produced largely unsuccessful results except in several cases in which large numbers were released frequently into indoor confined systems. Use of predators has involved some attempts at augmentation, but adopting cultural methods which favour predators and inhibit flies has shown considerable success. Use of competitors and pathogens is also reviewed. It is concluded that biological control is considered an important component of livestock integrated pest management, and recommendations for further research are made.*

INTRODUCTION

Interest in biological control of livestock pests has increased over the past 20 years because of reductions in the number of available chemical control options, increased control costs, increasing insect resistance to pesticides, and increased public concern for food quality and safety. Biological control of livestock pests, particularly filth-breeding flies in the family Muscidae, has been extensively researched as an alternative to chemical control (Patterson and Rutz 1986, Patterson 1981). Biological control of mosquitoes, blackflies, and ticks, which also include important livestock pests, is discussed in another paper in this workshop (Shemanchuk 1991).

Biological control is considered to be "the regulation of plant and animal numbers by natural enemies" (Wilson and Huffaker 1976). Natural enemies are usually thought of as parasitoids, predators and pathogens. In the case of dung-breeding flies, competitors also can be included as these regulate pest numbers by competing for a non-economic resource such as dung.

PEST OVERVIEW

The major pests of livestock in the family Muscidae are the horn fly, *Haematobia irritans* (L.), the stable fly, *Stomoxys calcitrans* (L.), the house fly, *Musca domestica* L., and the face fly, *M. autumnalis* DeGeer. These insects have similar life cycles. Adults lay eggs in batches every 2–3 days following a period of preovipositional development. Eggs are laid in decaying organic matter, usually manure, and hatch within a day. Three larval instars are completed in a short period, 5–8 days, followed by a pupal period of longer duration, from 40 to 60% of the total immature developmental time. Survival is lowest in the egg and first instars, and is higher in the larger larval and pupal stages. The pupa is enclosed in the hardened last larval skin, which forms the puparium. Following eclosion, adults pass through a brief teneral period while the cuticle hardens; they mate after 1–2 days. Adult survival is variable, but a proportion of females will survive long enough to undergo two and sometimes more ovipositions. From 20 to over 100 eggs per oviposition are produced depending on the species.

Axtell (1986) classifies livestock production systems in three categories: 1) pasture or rangeland, 2) outdoor confined and 3) indoor confined. Fly and natural enemy fauna varies between these systems because of different characteristics of manure composition and accumulation. Manure in pastures is well dispersed in discrete units, or pats. It tends to dry rapidly and forms a crust soon after deposition, which limits the amount of time each pat is available for colonization by flies and natural enemies. Both the horn and face flies are restricted to breeding in manure from grass or hay-fed cattle, and are considered as pests primarily in rangeland or pasture systems. Horn fly adults rest exclusively on the host, leaving only to oviposit in freshly dropped manure. Once a crust has formed, usually within an hour, the pat is no longer suitable for oviposition. Adults blood feed, and can cause economic losses at densities as low as 12 flies per animal. The face fly adult rests primarily along fence lines and vegetation. Adults feed by sponging secretions near the eyes and mouth of the cattle. Oviposition also occurs in freshly deposited pats. The larvae leave the pat upon completion of development and pupate in drier areas. The puparium is unique in that is mineralized. Both horn and face flies have a true diapause stage. The horn fly diapauses as a pupa in the pat, whereas the face fly diapauses as an adult in buildings and attics.

Cattle in outdoor confined systems are usually fed a more concentrated diet, with higher grain or silage and less hay than pasture animals. The resulting manure tends to accumulate under fencelines and around feeders. The high organic matter in the manure favours survival of house and stable fly larvae. As a result, these are pests primarily in confined cattle operations such as dairies and feedlots. Neither insect spends much time on the host. The stable fly visits the animals periodically for short periods to take a blood meal. The house fly feeds on manure and filth. Adults spend much of the time resting on surfaces. Neither species has a true diapausing stage, and both overwinter as slowly developing immatures or adults in warmer habitats.

Indoor confined systems, such as hog and poultry houses, can support large populations of house flies. Manure in these systems accumulates over long periods of time, usually in a pit beneath the animals. Manure is more easily managed in these systems.

PARASITOIDS

The most common parasitoids of livestock pests are parasitic Hymenoptera in the family Pteromalidae. These are small wasps that parasitize the pupal stage of the host. The female wasp inserts the ovipositor into the puparium, and lays one to several eggs on the pupa. The developing larvae feed on the pupa and kill it. Usually only one wasp emerges per parasitized pupa, except for *Nasonia vitripennis* (Walker), which can produce 1–10 adults per pupa, averaging 5. The stinging action of the female during oviposition can also kill the host, even if no parasitoid develops. These parasitoids are commonly reported to use the house, horn and stable flies as natural hosts. Natural parasitism levels in fly populations vary with the season, type of production system, and geographic location.

The predominant species attacking the house fly in the United States are *Muscidifurax raptor* Girault and Sanders, *Spalangia cameroni* Perkins, *S. endius* Walker, *S. nigroaenea* Curtis, and *Pachycrepoideus vindemiae* (Rondani) (Axtell and Rutz 1986). Parasitism levels can reach 30% or higher and are usually higher in confined systems than in pastures (Rueda and Axtell 1985). Activity is highest in July and August in southern areas. However, in colder climates, the predominant species are reduced to *N. vitripennis* and *M. raptor* (Rutz and Scoles 1989), with the highest abundance in August and September. This also has been observed in dairies in Alberta during 1989 (Lysyk, unpublished). *M. raptor* populations peaked in late June at 6% parasitism, and also in mid-August at 22% parasitism. *N. vitripennis* populations showed a single peak in August at 6% parasitism.

The parasitoid fauna associated with horn flies consists mainly of members of the genus *Spalangia*, particularly *S. cameroni*, *S. nigra* Latreille, and *S. nigroaenea* (Combs and Hoelscher 1969, Thomas and Morgan 1972, Thomas and Kunz 1986). Parasitism levels are usually low, averaging 4–11% throughout the season. Parasitism tends to increase in late summer and can reach as high as 40–50%. Parasitoid-induced mortality has been estimated at 7–10% in diapausing horn fly pupae (Thomas and Kunz 1986). In Alberta, horn fly parasitoids in pastures consist mainly of *M. raptor* and *S. drosophilae* Ashmead (Depner 1968, Peck 1974). *S. drosophilae* is normally a parasitoid of smaller flies, and has difficulty emerging from the puparium of the horn fly. *S. haematobiae* Ashmead and *M. raptor* show low levels of parasitism (0–19% in horn fly pupae collected in British Columbia (MacQueen and Beirne 1974). *S. haematobiae* has been suggested to be primarily a parasitoid of non-pest Diptera such as the Sepsidae.

Parasitism in natural stable fly populations in Missouri is also low, averaging 2.5–7.8% over the season. However, parasitism increased in July, and reached as high as 50% (Smith et al. 1987). The most abundant species was *S. nigra*. Seasonal abundance of natural parasitism averaged 18–22 per cent in California (Meyer et al. 1990). *S. endius*, *S. cameroni*, and *S. nigroaenea* were most abundant, with *M. raptor* and *M. zaraptor* Kogan and Legner present but at lower levels. Again, relative abundance was highest May to July, and reached over 30% in these months.

It is clear from these studies that the parasitoid fauna in warmer, southern areas is more diverse than in colder northern areas. The parasitoid fauna in pastures is also less diverse, and parasitism rates lower, than in confined systems (Rueda and Axtell 1985). Seasonal abundance of parasitoids is low in the spring and fall, but can peak at appreciable levels in the summer. Low spring populations are a result of high overwintering mortality (Guzman and Petersen 1986). Since parasitism can reach high levels, inundative releases of parasitoids have been attempted to aid in fly control. The parasitoids are easily reared using housefly pupae as a host and can be obtained for release from local distributors.

Biological control attempts using augmentative releases of parasitoids have produced variable results (Axtell 1986). Successes usually have been associated with indoor confined systems such as poultry houses or hog barns. Attempts in outdoor confined systems, such as dairies or feedlots, have not demonstrated effective control (Petersen et al. 1983, Meyer et al. 1990) because conditions are more variable than in indoor confined systems. Successful fly control has been achieved in Canada using commercially available parasitoids. Releases of 100,000 *S. endius* at 3-week intervals starting April 20 1978 into a deep pit poultry layer barn resulted in a decline of fly index from 35.7 spots per card to 20–30 spots per card throughout the trial, while in a nearby control house, fly activity rose from 43.5 to over 200 spots per card. Parasitism of collected fly pupae reached 63% (Costello 1984). Several species were introduced into an enclosed hog barn in Alberta (Weintraub 1985). Releases of 20–30,000 *M. raptor* every 2 weeks resulted in a steady decline of fly numbers over a 10-week period. Low levels were maintained for 8 weeks after releases suspended, then increased. Additional releases resulted in reestablishing the low level. Releases of combinations of *S. endius* and *N. vitripennis* were less effective.

Several problems need to be addressed before control can be made more predictable. The number of parasitoids per host has not been determined, and would be difficult to control because of the variable numbers of parasitoids in shipments. Commercially available parasitoid shipments may contain far fewer parasitoids (as low as 50%) than the promised yield (Stage and Petersen 1981). The timing and number of releases have not been adequately defined. Parasitoid development is 2–3 times longer than host development (Butler and Escher 1981); therefore releases have to be conducted frequently. Parasitoid species also differ in their ability to use specific hosts. For example, *M. zaraptor* does not parasitize stable fly pupae as readily as house fly pupae. Also, the strains provided may be shipped from great distances and not adapted to conditions in the area of release (Meyer et al. 1990).

Since *M. raptor* occurs naturally in Alberta, and has provided at least one success (Weintraub 1985) in controlling house flies in an indoor confined system, it would be worthwhile to establish a local strain and evaluate the potential of this strain for biological control in indoor and outdoor systems. Inundative releases in pasture systems for horn fly control may require some manipulation of the herd before successful biocontrol could be achieved. For example, it may be worthwhile to combine releases with a pasture rotation schedule so that releases can be made over a relatively small area of land. Also, orienting releases to maximize impact on the diapause stage of the horn fly may be most useful, as this would reduce the size of the population that can successfully overwinter and reduce the potential for early spring population increases. In order to achieve this, a more thorough understanding of diapause in the horn fly is required.

The major parasitoids of the face fly are the braconid *Aphaereta pallipes* (Say), the cynipid *Eucoila impatiens* (Say), and the staphylinid *Aleochara bimaculata* (Gravenhorst). Parasitism by *A. pallipes* is generally low in field populations of face flies, less than 15% (Blickle 1961, Thomas and Wingo 1968, Houser and Wingo 1967, Kessler and Balsbaugh 1972, Figg et al. 1983). Substantial mortality due to this parasitoid can occur in late summer and fall (Benson and Wingo 1963). The wasp has been reared successfully, but is not a suitable biological control agent for face fly because 1) laboratory production is not consistent, 2) adults are very short-lived, 3) it prefers other non-pest Diptera as hosts, including larvae of *Ravinia*, which are predators of face flies (Pickens 1981), and 4) it cannot emerge successfully from the calcified puparium of the face fly. Parasitism of the face fly appears to be accidental.

Eucoila impatiens also shows low levels of parasitism in face fly populations, less than 5%, but has reached levels of 28%. It is most active during July and August. No attempts at rearing or release have been made.

Aleochara bimaculata is actually a predator-parasitoid. Adults can feed on fly eggs and small larvae, and first-instar staphylinids enter the host puparium and feed on the developing fly pupa. This species occurs in quite low abundance in North America (Thomas and Wingo 1968, Kessler and Balsbaugh 1972,) and has minimal impact on the face fly. However, a related species, *A. tristis* Gravenhorst, was found attacking face flies in Europe and sent to the USA for release. Releases were made in Nebraska (Wingo et al. 1967) and California (Legner 1978). The beetle was established, but does not appear to provide any degree of control as it has a limited ability to find face fly immatures, is not able to emerge from the puparium, and tends to prefer parasitizing non-pest Diptera.

PREDATORS

Predacious arthropods can inflict heavy mortality on fly populations, regardless of the system. Predators have been shown to reduce production of house flies 31–98% (Axtell 1963), stable fly production by 71% (Smith et al. 1985), horn fly production by 75–95% (Blume et al. 1970, Kunz et al. 1972, Thomas and Morgan 1972, MacQueen and Beirne 1975b) and face fly production by 50–70% (Burton and Turner 1970, Thomas et al. 1983). As a result, there is considerable interest in the use of predacious arthropods for control of flies. Extensive research programs are under way for the importation and use of predators for control of horn fly in Texas and also for the control of house flies in poultry houses in North Carolina. A new research initiative is under way at the Lethbridge Research Station to identify potential predators of the horn fly in southern Alberta.

Confined systems The major predators of house flies in indoor confined systems are mites in the family Macrochelidae, particularly *Macrocheles muscadomesticae* (Scopoli), as well as beetles in the family Histeridae such as *Carcinops pumilo* (Erichson). These naturally occurring predators can consume large numbers of eggs and first instars of house flies, up to 104 and 21 per individual, respectively (Geden et al. 1988). Predation is reduced by lowered temperatures, limited prey availability, and alternate prey. Natural populations of these predators can be facilitated by 1) keeping manure as dry as possible, 2) staggering manure removal and leaving a base of old manure to absorb moisture and provide a recolonization source for predators, and 3) using selective insecticides and avoiding larviciding (Axtell 1986). Augmentation by release of these predators has been attempted, and can reduce house fly production by 86 to 98% (Axtell 1963). A mite to fly egg ratio of 1:5 can reduce house fly production by 85 to 90% (Singh et al. 1966). *Macrocheles* shows considerable promise as a biological control agent as these mites have a short developmental time, high attack rate, can survive on alternate prey, and can be reared in large numbers in the laboratory (Geden et al. 1990). The mites are phoretic on the fly host and, as a result, can colonize new areas rapidly.

Other species of muscoid flies have been promoted for biological control of house flies. The black garbage fly, *Ophyra aenescens* (Weideman), has breeding habits similar to those of the house fly, but has predatory habits as a third instar larvae. This species is capable of destroying 7–30 house fly larvae per day (Geden et al. 1988). The black garbage fly has been observed to replace house flies in poultry houses (Nolan and Kissam 1985, Lysyk and Axtell 1986). Multiple seeding of *O. aenescens* into high-rise poultry houses resulted in reductions in house fly numbers of 30–45% relative to controls (Turner and Carter 1990). The black garbage fly is easily reared and has been recommended for use as a biological control agent for house fly because the adult apparently remains close to the manure pit (Turner and Carter 1990) and does not migrate from poultry houses (Nolan and Kissam 1987). However, a related species, *O. leucostoma* (Weidemann), has been reported to fly great distances. Release of the proper species is therefore essential. Also, the producers must be educated and willing in order to accept the presence of *O. aenescens* rather than the house fly.

Vertebrate predators also have shown promise for fly control in confined livestock operations. Cockerels released in shallow-pit poultry houses gave adequate fly control by feeding on larvae and pupae provided that manure was kept dry and the cockerels were kept hungry by denying them access to feed (Rodriguez and Riehl 1962). The major problems were that wet manure favours fly production and inhibits the cockerel's ability to find fly immatures. Wet manure can ball on the cockerel's legs, making it difficult for them to move and can result in higher mortality. Also, this project was conducted in a housing type which is in little use nowadays. Most poultry are produced in deep-pit houses, which have much larger areas of inaccessible manure.

Recently, use of Muscovy ducks as predators of adult flies has been evaluated in small-scale laboratory and preliminary field trials (Glofcheskie and Surgeoner 1990). These ducks readily feed on flies and can quickly remove them from a small area. The success of capture attempts averages 70%. The ducks offer the advantages that they could provide season-long control, they are mobile, and have been accepted readily by producers. However, they do not feed on maggots, and are unlikely to be able to reach flies at heights above 1 m. There is also the risk of disease transmission. Use in outdoor facilities may be difficult as the ducks might disappear by dispersal and predation if not confined. Nonetheless, use of Muscovy ducks does merit further critical investigation.

Pasture systems The major predators in pasture systems belong to the Coleoptera families Staphylinidae and Histeridae. One of the most important genera of Staphylinidae is *Philonthus*, which is capable of reducing face fly production by 73% (Kessler and Balsbaugh 1972) and horn fly production by 87% (Roth et al. 1983). A related species, *P. flavolimbatus* Erichson, can reduce horn fly production by 72% at a ratio of 1 beetle per 10 horn fly eggs (Harris and Oliver 1979). These predators are able to arrive at a pat soon after its deposition and search actively within the pat and underneath for fly eggs. Adults will fly in both open and wooded pastures (Hunter et al. 1986). The species is active early in the fly season (MacQueen and Beirne 1975b) but declines in mid summer (Roth et al. 1983). Densities in the field are low, less than two per pat (Roth et al. 1983), which also limits activity as a fly predator. They also are opportunistic and feed on the most available prey, which may not necessarily be pest flies. However, they can be reared in the laboratory and if mass-production techniques can be developed, could be quite useful as predators of horn flies. *P. cruentatus* Gmelin is abundant in Canada (MacQueen and Beirne 1975b) and appears to be an excellent candidate for future work.

Histerid beetles, such as *Hister abbreviatus* F. and *H. coenosus* Erichson also can cause heavy mortality of face fly and horn fly eggs and first instar larvae (Kessler and Balsbaugh 1972, Summerlin et al. 1982), but appear to be of limited effectiveness in field populations because of their low population densities.

Mortality caused by egg-larval predators is important, but these are the stages which typically have the highest mortality in the absence of predation. Since the pupal stage is relatively well protected, additional mortality caused by the introduction of a pupal predator could be of great value in reducing populations. For example, the histerid *Pachylister chinensis* (Quensel) has provided control of buffalo fly populations in Fiji (Bornemissza 1968). Adults feed on maggots and lay eggs in the pats. The eggs hatch while the flies are large larvae or pupae, and the histerid larvae are predacious on these stages. Synchrony of the predator's life cycle with the late-larval and pupal stages of the host seems important. A related species, *P. caffer* Erichson, has been imported to the United States from South Africa. It also is well synchronized with the pupal stage of the host, and can consume 6–7 horn fly pupae per day (Summerlin et al. 1989). Establishment of the species in the U.S. is presently being attempted. Inoculative releases may be successful in the southern U.S. but unless the insect can overwinter in Canada, this release strategy will be of limited value. Repeated inundative releases may be worthwhile, however, rearing of histerids is difficult due to cannibalism, reluctance to feed, and inhibition of mating due to confinement (Summerlin 1989).

Although predators can cause high mortality in laboratory studies, their efficiency in the field is reduced. Predators do not enter every pat in the field (Summerlin et al. 1982), which may be due to their low abundance. The most abundant predators seem to be those that enter the pat soon after its deposition (Wingo et al. 1974) and feed on the eggs and small larvae. There is a scarcity of predators on the pupal and large larval stages. Release of these should be considered, and would likely be beneficial as mortality in the large larval and pupal stages could be considered as additional mortality. Predators select prey according to size (Burton and Turner 1970); egg predators and pupal predators do not compete for the same resource.

Most attention has focused on the Coleoptera; however, other groups also may be significant. The role of mites as predators of the horn fly has not been fully evaluated. Mites phoretic on dung beetles can cause reductions in fly survival by feeding on eggs and small larvae (Tyndale-Biscoe et al. 1981). The effect of these mites is to enhance the action of dung beetles on control. These studies were conducted against the Australian bush fly, *Musca vetustissima* Walker, but there is no reason why similar potential should not exist for horn fly control in Canada. Macrochelid mites, *M. glaber* (Müller), are phoretic on *Aphodius* dung beetles (MacQueen and Beirne 1974) in Canada, and could possibly be released using the dung beetle as a carrier.

Several species of non-pest flies that occur in pastures have larvae which are predacious on larvae of pest flies, much as *O. aenescens* is in confined operations. *Ravinia lherminieri* (Robineau-Desvoidy) is a sarcophagid fly whose larvae is capable reducing survival of face fly eggs by 98% in laboratory trials (Pickens 1981). Efficiency of predation decreases with increasing age of the host and volume of manure. However, the species can survive in the absence of the host and the adults are highly mobile. The use of non-pest Diptera in pastures should be considered, but the same cautions that apply to confined livestock situation apply. As well, there is the additional concern that mass introduction of a new species may diffuse the effect of other predators on the pest species. Whether or not this would occur largely depends on the host preference of the native predators (Muirhead-Thomson 1988). Again, *Ravinia* shows potential as it larviposits; the advanced stage of its larvae relative to the pest species would offer it some protection from other predators.

COMPETITORS

Dung fauna in North America is poorly developed relative to that in other parts of the world. About 50% of the dung fauna is introduced (MacQueen and Beirne 1974). Lack of dung fauna has been suggested as a major reason why introduced fly species, such as the horn fly, have been able to breed so successfully here. The dung itself is a waste product, and in the absence of a decomposing fauna, will remain in the system for a long period. This represents nutrients lost to the system and a reduction in total acreage available for grass production. In addition, growth near dried pats tends to be rank and unpalatable to cattle (Waterhouse 1974). Since the dung itself is a waste product of limited commercial value, extensive programs have been initiated in Texas and California to release dung beetles to disperse dung and also to provide control of dung-breeding pests such as horn flies and gastrointestinal worms (Anderson and Loomis 1978). These programs have been patterned after an earlier program in Australia, which was oriented toward control of the bush fly and buffalo fly.

Removal of cattle manure by dung beetles potentially affects fly populations in several ways. Mortality and developmental time of fly larvae can be increased by reduction in breeding habitat. Lowered food also results in a reduction in body size of the flies and a corresponding decrease in the reproductive potential of the pests. The burrowing activity of the beetles can enhance the action of predators and parasitoids by disrupting the protective crust and allowing access to the flies. Drying of the dung is also promoted which renders it unsuitable for fly development. Fly larvae also may be concentrated in smaller areas and the effectiveness of predators enhanced. Introduction of dung beetles has been accomplished in Hawaii, Australia, Texas and California. *Onthophagus gazella* F. was introduced to Hawaii in the late 1950's. These beetles are capable of burying large amounts of dung in a short period of time, up to 1 litre in 60 hours, at low densities, 15 pairs per pat. Horn fly breeding was substantially reduced in areas in which the beetle occurred but it only colonized pats in open pastures and had no effect on breeding in wooded areas. CSIRO has imported over 40 species of dung beetle to Australia, of which less than half have become established. Biological control of the bush fly has met with limited local successes (Muirhead-Thomson 1988). *O. gazella* has colonized much of northern and eastern Australia. *Euoniticellus intermedius* Reiche and *E. africanus* Harold were established in southern Queensland and New South Wales. These introductions have provided some degree of fly control (Hughes 1975), but the beetles are not in complete synchrony with the fly-breeding season. They become active in the spring somewhat later than the flies and activity ceases in fall before the flies' does (Waterhouse 1974). It is possible to obtain good fly control if the beetles remain until the end of the fly season (Hughes et al. 1978). Overall, fly populations were not significantly reduced after the introduction of the competitors, even though dung-burial is extensive. *O. gazella* and several other species of dung beetles were introduced into Texas and are capable of removing 80% of the dung from fly-breeding areas during peak activity (Harris 1981). High activity occurs in the early summer some time after horn flies become active, decreases during the late summer and ceases in the fall before the fly-breeding season is over (Roth et al. 1983). Releases also have been made in California and although dung burying activity is extensive, fly populations persist and remain at high levels (Legner 1986).

It appears that effective use of dung beetles for biological control of flies has not been achieved, likely for the following reasons. Flies can complete normal development in very small amounts of dung. Only 2–3 grams per larvae are required (Moon 1980). The beetles are not present in sufficient numbers during the fly season or throughout the fly habitat to be able to reduce the amount of dung sufficiently. There also is some suggestion that horn fly larvae may be able to complete development in buried or partially buried dung. By the time the dung-burying beetles arrive at a pat and start to remove it, eggs have hatched and first instars are present (Legner 1986). Because of the rapid development of fly eggs and larvae, a pat would have to be completely buried within a week. The pupal stage is quite capable of surviving in the absence of manure. Some species, such as *O. nuchicornis* (L.), only bury portions of the pat, leaving enough for fly larvae to develop (MacQueen and Beirne 1975a). The flies breed both day and night; beetle species with both diurnal and nocturnal flight habits are required. The requirements for establishment of dung beetles and removal of dung are high. At least 8–10 species of dung-beetle are required in a pasture to bury cattle manure as soon as it is deposited (Fincher 1986). An estimated 120 species are required to cover the different climatic regions, soil and habitat types in Australia (Ferrar 1973). There also has been some suggestion that dung-burying beetles and predatory beetles are incompatible because dung-beetles disrupt the habitat (Legner 1986). High dung-beetle numbers can inhibit reproduction by predatory beetles (Roth 1983). However, not all dung beetles bury dung, some burrow into it. One species of these, *Aphodius*, arrives soon after the pat is deposited (Mohr 1943) and is known to carry a macrochelid mite which can act as a predator on fly eggs (MacQueen and Beirne 1974). This type of interaction could be exploited for fly control in pastures.

PATHOGENS

Information on pathogens affecting livestock insects is scanty and much work remains to be done in this area. The effect of entomogenous nematodes on various stages of house fly has been studied in the laboratory (Geden et al. 1986). *Steinernema feltiae* (Filipjev) Wouts et al. and *Heterorhabditis heliothidis* (Khan et al.) are capable of infecting and killing larval and adult house flies if the hosts are exposed on filter paper. Infectivity of larvae decreased in a rearing medium substrate and was very low in a poultry manure substrate; thus these nematodes have limited potential for controlling fly larvae in indoor confined systems. These observations are consistent with those of Renn et al. (1985). Field trials in poultry houses have not demonstrated any control potential (Mullens et al. 1987). Nematodes can be effective in soil substrates (Geden et al. 1987), therefore there is a possibility that nematodes may be effective in substrates such as cattle manure or horse manure, but this has not been studied. Both species are capable of infecting adult flies and causing substantial mortality if presented as baits (Renn et al. 1985, Geden et al. 1986). The nematodes are presented in a bait disc impregnated with an attractant compound. Flies feeding on the discs are infected and die within 2–4 days. This method has not been evaluated in the field.

The nematode *Heterotylenchus autumnalis* Nickle infects face flies and causes sterility in adult flies. It has been estimated that a completely infected face fly population would have 23% of the reproductive capability of an uninfected population (Krafsur et al. 1983). Infection rates in field populations are low, but increase with cooler weather. The nematode can overwinter in infected females, so late-season introductions may be capable of reducing breeding in the spring (Treece and Miller 1968). The species can be cultured in the laboratory (Stoffolano 1973) and at least one field trial of releases of over 10,000 parasitized pupae has been made. The results of this trial have not been reported, but it has been claimed as a success (Legner 1978).

House flies and some other filth flies are susceptible to infection by the fungus *Entomophthora muscae* (Cohn) Fresenius. Infection rates are usually highest in the fall and under some circumstances can be quite substantial, over 45% (Mullens et al. 1987). The fungus releases secondary conidia from cadavers attached to south-facing vertical surfaces. These secondary conidia are believed responsible for the increase in fall infections as adult flies increasingly rest on sunny surfaces during cool weather, therefore increasing their risk of infection. High temperatures also inhibit development of the pathogen and infections are rare in the summer. Although no method for applying this pathogen is presently available, natural infestations can be promoted in the fall by avoiding spraying of southern exposures with insecticides. Insecticides reduce conidial discharge and prevent healthy flies from becoming infected and propagating the disease (Mullens et al. 1987).

Rare natural infections of house flies by the pathogen *Beauveria bassiana* Vuillemin recently have been reported (Steinkraus et al. 1990). Mortality of adults is substantial if they are fed conidia on sugar, sprayed with a suspension, or treated with 2-year-old conidia. The fungus is available commercially and has a long storage life, which makes it attractive. Strains of the fungus vary in their infectivity to insects, so it remains to be determined if commercially available products are infective to flies. Nevertheless, this could prove to be a fruitful area for future research.

Pathogens may not be able to adequately control larval fly populations because of the substrate, but would be very useful against adults. Pathogens that can limit reproduction either by castration or by reducing female survival would be extremely useful. Since flies have such a high reproductive capacity, focusing attention on control of immature stages might not be as productive as focusing on the adult. Unfortunately, few natural enemies of adult flies are known. Without reducing the reproductive capability of the adults, the potential for complete biological control of fly populations seems remote. However, it should be kept in mind that biological control agents have proven to be extremely effective in integrated pest management of livestock pests. Further research to find, evaluate and promote biological control agents is essential, particularly in light of the restricted number of chemical control options available.

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Biological Control of Urban and Domestic Pests

J.A. Shemanchuk
Agriculture Canada, Research Station, PO Box 3000, Lethbridge, Alberta T1J 4B1

ABSTRACT *Urban and domestic pests include a wide range of arthropods. In this paper the state of the art of biological control in Canada is presented for mosquitoes, black flies, cockroaches, bed bugs, ticks, cluster flies, lice, fleas, ceratopogonids, tabanids and food product pests. In Canada, only a few biological control agents have been sufficiently studied to determine their potential. The areas worthy of research are identified.*

INTRODUCTION

Urban and domestic pests include a wide range of arthropods. In this presentation I consider mosquitoes, black flies, cockroaches, bedbugs, ticks, cluster flies, lice, fleas, ceratopogonids, tabanids, and food product pests. This list is not intended to be complete and perhaps some very important pests have been left out. Others such as ants, termites, slugs, and box elder bugs could be classified as urban and domestic pests.

MOSQUITOES

Mosquitoes are at the top of the list of urban pests because in Canada they are abundant, widely distributed, and troublesome. Mosquitoes usually breed in a rural environment but invade the urban environment to obtain nutrients to propagate the species. In spite of very effective chemical controls, mosquito nuisances are still with us. The problems of increased costs of insecticides, the increased risk of damage to the environment, and the increased spread of resistance to chemical pesticides have diverted greater attention to biological control.

In Canada, progress in biological control of mosquitoes has been slow, due in part to lack of funding and the complexity of the problem.

Bacteria The greatest progress in biological control of mosquitoes has been made in the use of a bacterium, *Bacillus thuringiensis* Berliner var. *israelensis*. Several larvicidal formulations of this bacterium registered in Canada are being used in many urban communities with varying degrees of success. This bacterium acts as a stomach poison and has to be ingested in sufficient quantity to be effective. It is more effective against *Aedes*, *Culex*, and *Culiseta* species than against *Anopheles* because of their feeding habits. The bacterium does not persist in the larval environment for long periods of time; thus, it has to be applied repeatedly as new larvae appear. It also settles to the bottoms of ponds where it adsorbs to plants and organic matter and is not available to the larvae. In spite of these limitations, *B.t. israelensis* is presently the best biological control available in Canada, and perhaps with some manipulation of formulations it can be improved.

Fungi Aquatic fungi, *Coelomomyces* spp., have been considered as potential biological control agents for mosquitoes in various parts of the world since about 1920. *Coelomomyces* was first reported in Canada by Hearle (1929) in an adult of *Aedes flavescens* (Müller). In 1959, Shemanchuk (1959b) reported on the discovery of *Coelomomyces psorophorae* Couch in 12% of *Culiseta inornata* (Williston) larvae collected in southern Alberta. *Coelomomyces* have since been reported from larvae and adults of several *Aedes* spp. and *Anopheles earlei* Vargas from various locations in Alberta, Saskatchewan and Manitoba (Shemanchuk 1977, 1980, Taylor et al. 1980, Harlos pers. comm. 1990).

The work of Whisler et al. (1974, 1975) revealed the presence of an intermediate host, a copepod, *Cyclops vernalis* Fischer, in the life-history of *C.*

psorophorae. This discovery led to the successful laboratory propagation of the fungus and to the understanding of some of its basic biology. Since the discovery of the life cycle of *C. psorophorae*, life cycles of other species of *Coelomomyces* have been worked out (Couch and Bland 1985). Each *Coelomomyces* species has a different intermediate host. For example, *C. psorophorae* requires the copepod and *Coelomomyces utahensis* Romney, Couch and Nielsen requires an ostracod as the intermediate host to complete their life cycles.

In our laboratory we are now able to maintain in vivo cultures of *C. psorophorae*, *C. utahensis*, and *Coelomomyces stegomyiae* Keilin. At present, we are producing a sufficient quantity of *C. utahensis* for laboratory and field experiments. This species is easy to produce in quantity because its herbivorous intermediate host is easy to rear in the laboratory. *C. psorophorae* is more difficult to maintain because copepods are carnivorous and require special, laborious rearing techniques. Sabwa (1988) and Shemanchuk and Whisler (1988) demonstrated that in artificial laboratory ponds the fungus can remain infective for up to 12 weeks if the fungus is allowed to recycle. A single inoculation can be infective for about 22 days. These results indicate that *C. utahensis* could have application for mosquito control as a biological insecticide or as an inoculum in mosquito-breeding sites where the fungus could establish and maintain itself.

Taylor et al. (1980) and others (Hearle 1929, Sabwa 1988, Harlos pers. comm. 1990) reported finding female mosquitoes infected with sporangia of *Coelomomyces*. This is a feature that is important to the spread of the fungus between mosquito habitats and is a desirable attribute of this pathogen.

The advantages of *Coelomomyces* as biological control agents for mosquitoes are that they are target specific, they produce high mortalities, they survive drying and freezing, and they can be produced in vivo in quantity. *Coelomomyces* spp. can be used as a microbial pesticide in the form of a suspension of zygotes that can be applied as an inundative pesticide to mosquito larval populations, or they can be used to inoculate semi-permanent or permanent ponds containing mosquito larvae where sporangia and the respective intermediate host take advantage of the recycling characteristic. More study is needed under field conditions on the biological interaction of *Coelomomyces* with the hosts under stress of all the biological components in mosquito habitats. *Coelomomyces* may not be a control for mosquitoes by itself but it has the potential to be a significant component in an integrated management program in some Canadian regions.

Other fungi, namely *Culicinomyces clavisporum* Couch, Romney and Rao , *Saprolegniales* sp. and *Smittium* sp., were found in mosquito larvae in Alberta (Goettel 1987a). These pathogens had little effect on the larval mosquito populations studied.

Goettel et al. (1984) reported the occurrence of *C. clavisporum* in mosquito larvae from Alberta, which is the northernmost geographic record to date. The significance of this discovery is that this pathogen is established in Alberta and is capable of survival. The ability of this pathogen to survive Alberta climatic conditions and to produce and disperse conidia under water is a combination that should be investigated to determine its potential as a biological control agent for mosquitoes.

Goettel (1987b) reported on infections with a California strain of *Tolypocladium cylindrosporum* Gams in five species of mosquitoes under field conditions. Infections occurred up to 29 days after application of blastoconidia and conidia. No infections were detected in subsequent years, indicating that there is no residue from inoculations. Further study is required on the fungus-host relationship before the full potential of this pathogen can be assessed.

Nematodes Nematodes in adult mosquitoes have been found in Canada in British Columbia (Hearle 1927, Trpis et al. 1968) and Manitoba (Galloway and Brust 1976b). Jenkins and West (1954) reported a heavy infestation of nematodes in larvae of *Aedes communis* (DeGeer) and suggested that these nematodes may be effective in natural control of mosquitoes. Welch (1960b) described a new species of nematode, *Hydromermis churchillensis*, which killed between 10 and 80% of larvae of *Ae. communis* in pools at Churchill, Manitoba. Galloway and Brust (1982, 1985) conducted extensive laboratory and field experiments with the nematode *Romanomermis culicivorax* Ross and Smith and concluded that widespread use of this nematode is impractical. However, they suggested that, because of the ease of rearing, this nematode may have a place in locations where the use of chemical or bacterial agents is undesirable (Galloway and Brust 1976a). Further research is needed in the area of field application of *R. culicivorax*. The high degree of host specificity and the possibility of environmental adaptation to temperate climates make it an alternative worthy of further investigation.

Trematodes Rau (1989) found a broad range of mosquito species affected by an entomophilic digenean, *Plagiorchis noblei* Park. The introduction of cercaria-producing snails into a *Culex pipiens* L. breeding habitat resulted in almost complete control. Daily exposure of *Aedes aegypti* (L.) to cercariae of *P. noblei* in concentrations as low as 200 per litre of water provides almost total control. In the field, cercariae regularly attain 30 times this concentration. Entomophilic digeneans, with further study, may provide a novel and valuable adjunct to integrated management of mosquito pests.

Protozoans Of the protozoan parasites, microsporidians have been found in larval and adult mosquitoes, but little is known about their life cycle and their effects on Canadian mosquitoes. Harlos (1981) reported the occurrence of microsporidia in larvae and adult mosquitoes from Alberta. It is not known whether the microsporidia found in adult mosquitoes are the same as those found in larvae. Welch (1960a) reported the effects of protozoan parasites and commensals on larvae of *Aedes communis* (DeGeer) at Churchill, Manitoba.

Viruses There are three main groups of viruses in mosquitoes (Service 1983): iridescent viruses, nuclear polyhedrosis viruses, and cytoplasmic polyhedrosis viruses. To date, very little success has been realized in using these viruses as biological control agents for mosquitoes. A survey of natural habitats would be useful to establish the occurrence, distribution and effects of these viruses on mosquito populations.

Predators Various vertebrates and invertebrates prey on mosquitoes. Mosquitoes may be consumed as larvae and pupae in their aquatic environment and as adults outside the aquatic environment. In the aquatic environment they are subject to predation by fish, insects, flatworms, snails, and amphibians. James (1961) reported that Ontario woodland pools contained 17 species of aquatic insects and other animals, of which eight species of Dytiscidae, one of Hydrophilidae, one of Limnophilidae, and one species of pond snail were regarded as important predators of mosquitoes. Beetles, though present in mosquito habitats, were not effective as biocontrol agents because they consumed a small portion of the mosquito larval and pupal population before they completed their development. No quantitative data are available to show the impact of beetles on populations of mosquito larvae. Much more information is required on the bionomics of the various predators before their value as biocontrol agents can be evaluated.

The ghost larvae in the family Chaoboridae are widely distributed in Canada and are effective predators of mosquito larvae. *Mochlonyx velutinus* (Ruthe) has been reported as an occasional predator of mosquito larvae by James (1957). Numerous *Chaoborus* spp. have been reported from various parts of Canada (Twinn 1931, James and Smith 1958, Shemanchuk 1959a, Borkent 1980, Harlos and Taylor pers. comm. 1990). These predators are found in semi-permanent and permanent pools where they are effective in controlling mosquitoes. They are less effective against mosquito larvae in temporary pools. Borkent (1980) reported that *Chaoborus cooki* Saether readily consumed mosquito larvae under laboratory and field conditions. He further reported that in one pool in Alberta *C. cooki* completely eliminated a population of mosquitoes. Harlos and Taylor (pers. comm. 1990) described a procedure for colonization and mass production of two species of chaoborids, *C. crystallinus* and *C. americanus* (Johannsen). They reported that the consumption rate ranged between 1.97 and 6.73 mosquito larvae per fourth instar chaoborid larva per day. The combination of the ease of rearing and the high predation rates makes this predator an excellent candidate for further evaluation as a biological control agent for mosquitoes.

Planarians or flatworms, usually found in permanent and semi-permanent pools, are predators of mosquito larvae (George 1978, Harlos and Taylor pers. comm. 1990, Ramalingam 1990). Ramalingam (1990) reported that *Mesostoma ehrenbergii* (Focke) is widespread in central Alberta and is a voracious feeder on mosquito larvae, particularly in the absence of other invertebrate hosts. Attempts to colonize these flatworms in new habitats met with limited success. George (1978) reported that *Dugesia tigrina* (Girard) was effective in consuming *Culex* mosquitoes in rainwater catch basins. The rapid rate of reproduction, the acceptability of mosquito larvae as prey, and the non-migratory habit of the flatworms enhance the potential of these predators as mosquito control agents in rainwater catch basins, semi-permanent, and permanent pools. These predators should be a goal for further research.

Fish are known to consume mosquito larvae. The most commonly used fish are *Gambusia affinis* Baird and *Poecilia reticulata* Peters. These have not been used in Canada because of the climatic conditions.

There is one report that *G. affinis* was introduced into the hot spring pools in Banff, Alberta. The fish survived for several years but their effects on mosquitoes were not recorded (Mail 1954). Dixon and Brust (1971) showed in their laboratory experiments that the fathead minnow, *Pimephales promales* Rafinesque, readily preyed on mosquito larvae. In the field they maintained themselves on small crustaceans, algae and detritus when mosquito larvae were absent. Dixon and Brust (1971) also described a management procedure for this species of fish which might be used under field conditions. This species is indigenous to Canada and is a likely candidate for consideration as a biological control agent for mosquitoes.

Other possible predators of mosquitoes that have received no attention as possible biocontrol agents in Canada are adult dragonflies, adult damsel flies, spiders, bats, and insectivorous birds.

BLACK FLIES

Bacteria Like mosquitoes, black flies are subject to a variety of pathogens and predators. The common biological control agent used against black flies in Canada is *B.t. israelensis* (H-14) (Undeen and Nagel 1978, Undeen 1979a, Undeen and Berl 1979, Colbo and Undeen 1980, Undeen and Colbo 1980). Several formulations of this pathogen are registered in Canada and available commercially. These have been used for control of black flies in Saskatchewan, Manitoba, and Ontario (Galloway and Burton 1988, M.M. Galloway and P.G. Mason, personal communication). The variability in effectiveness reported may have been due to differences in the physical conditions of the black fly habitats. Factors such as flow rate, turbidity, substrates, water temperature, and feeding state of the larvae could affect the efficacy of the pathogen. *B.t. israelensis* is a stomach insecticide and, to be effective, has to be present long enough for the larvae to ingest a lethal dose. The varied formulations could be responsible for some of the variability in effectiveness. There is a need for research to improve the formulations for use in flowing water habitats.

Fungi Records of fungi affecting Canadian black flies are few. Phycomycetes were found in ovaries of several black fly species (Undeen and Nolan 1977, Undeen 1979b). Infected females produce no or very few eggs and apparently do not seek a blood meal. Attempts to culture isolated spores of these Phycomycetes were unsuccessful. Infection with this fungus does not kill the black fly, but it does interrupt the search for a blood meal. A fungus, *Entomophthora culicis* (Braun) Fresenius, parasitizing *Simulium venustum* Say and *Simulium vittatum* Zetterstedt was discovered in central Alberta (Shemanchuk and Humber 1978). This fungus occurs during the summer months and kills young black fly adults. *E. culicis* has the potential of being a biocontrol agent for black flies, because it is fatal and virulent to adult flies, it is established in the area, it can survive the local climatic conditions, and it is not specific within the family Simuliidae. It is an ideal subject for further study of its life cycle and behavior under field conditions, and for possible exploitation for biological control of black flies in Canada.

Nematodes Mermithid nematodes are commonly found in simuliid larvae and adults (Mokry and Finney 1977, Colbo and Porter 1980, Anderson and Shemanchuk 1987). Many authors have reported that mermithids reduce black fly populations. The life cycles are known for a few species but the specificity of nematodes to particular species of simuliids has not been extensively examined. Colbo and Porter (1980) showed that host specificity exists. The taxonomy of mermithids in black flies is not well understood. The lack of in vitro production of nematodes is hampering the use of nematodes as biological control agents for black flies. Finney (1981) described various methods of in vitro culture of some nematodes. For culture techniques to be more effective, more knowledge is needed about the host, the parasite, and their interrelationship. With this knowledge it may be possible to define and manipulate various types of media for maximum production. *R. culicivorax* can be mass produced in vivo and has been reported to kill *Simulium verecundum* Stone and Jamnback, but this nematode is not sufficiently infective to black flies for practical biocontrol (Finney and Mokry 1980). Since flowing water is the type habitat for black flies and *R. culicivorax* is a still-water species it is not likely that it would establish in black fly breeding grounds, and therefore it would have to be produced elsewhere and used as a biological insecticide applied directly to larvae in their habitats. This may prove to be impractical in flowing water conditions. Anderson and Shemanchuk (1987) reported an epizootic of a mermithid parasite, *Isomermis* sp., in adults of *Simulium arcticum* Malloch in central Alberta. This nematode was found in almost 50% of the flies examined. Although the flies were killed by the exit of the mermithid, this parasite is ineffective against the major pest species, *S. arcticum*, because it does not prevent parasitized females from seeking and taking a blood-meal and thereby harassing cattle. However, in years when nearly 50% of the emerged adult black flies are parasitized, this mermithid may be a principal factor regulating the population density of *S. arcticum* in subsequent years. A study of the life cycle and distribution of the immature stages of this nematode should be a goal for research. Most of the authors who recorded nematodes in black flies also stated that they regulate populations but none stated to what extent. Mermithid infections and their effects on simuliids are unpredictable. More research is needed to determine the factors that control distribution in the habitat. The taxonomy also needs more study. An understanding of the bionomics of the free-living stages of the nematodes in a flowing water environment could be a key to exploiting nematodes as a biocontrol agent for black flies.

Trematodes There are no records of trematodes as enemies of black flies.

Protozoa Vavra and Undeen (1981) identified seven clearly distinguishable species of microsporidia in black flies of Newfoundland. Microsporidia also have been found in Canadian black flies by Cameron (1922), Twinn (1939), and Undeen et al. (1984). In all of these reports the effects of the microsporidia on populations are not discussed. Since none of the spores found in black fly larvae have been transmitted from sick to healthy simuliids, it is speculated that an intermediate host may be involved in the life cycle. Transovarial transmission is speculated, which would be necessary for upstream transport of the disease. To evaluate the potential of microsporidians as biological control agents for black flies, more research on their life cycles is needed.

Viruses Viruses have not been recorded to the same extent in black flies as in mosquitoes and other insects. Three groups, iridescent viruses, cytoplasmic polyhedrosis viruses, and densonucleosis viruses, have been described in black flies, but the role of these viruses in populations of black flies is not clear. Mokry (1978) reported a high level of mortality in patently diseased laboratory-reared larvae that were ostensibly infected transovarially with cytoplasmic polyhedrosis virus. Bailey (1977) obtained up to 70% and 55% experimental infection of *S. venustum* and *Stegoptera mutata* (Malloch), respectively, but the results were erratic. Despite the wide host range and infectivity of the cytoplasmic polyhedrosis virus, Bailey (1977) concluded that it would be of little value in biological control of black flies. Erlandson and Mason (1990) described a new isolate of an iridescent virus from larvae of *S. vittatum* from Saskatchewan. More knowledge is needed on the types and behavior of the viruses in the host and their mode of infection before they can be assessed for biocontrol potential.

Predators Davies (1981) compiled a comprehensive list of predators of black flies, which includes mammals, birds, amphibians, fishes, insects, and invertebrates. Cameron (1922) and Twinn (1939) reported that the common sucker, *Catostomus commersoni* (Lacepède), is a natural predator of *Simulium* larvae. Predation on black flies is random, difficult to evaluate, and can occur in all life stages. Predators offer little promise for black fly control and at present none can be identified for study.

COCKROACHES

The significance of cockroaches as pests is recognized because they have been incriminated as transmitters of bacteria causing food poisoning and as hosts for flatworms and roundworms. In Canada very little attention has been directed at the possible medical significance. Cockroaches feed on a wide range of domestic wastes and foods and move readily between buildings and from sewers to dwellings. High infestations of cockroaches produce a disagreeable odor. This could become a problem in Canada in urban environments, particularly in apartment complexes that are centrally heated and have frequent changes of occupants. To date there are no records in Canada of attempts to control cockroaches using biological control agents. Ulewicz (1975), in Poland, showed that *B.t. thuringiensis* was pathogenic to *Blattella germanica* (L.) and that nymphs were more susceptible than adults. Mortality occurred 12-20 days after infection and the *Bacillus* was transmitted to the population as a result of cannibalism. Oswald and Minter (1980) and Minter and Oswald (1980) tested a nematode, *Neoaplectana carpocapsae* Weiser, against *B. germanica* and found that this nematode kills its host with the aid of its symbiotic bacterium. This nematode was effective, but at very high doses. Biological control of cockroaches presents a very interesting challenge for research in urban environments.

BEDBUGS

In recent years there has been an increase in bedbug infestation in urban environments in Canada. This increase can be attributed to an increase in the number of multiple-dwelling complexes and greater mobility of people. Both sexes of bedbugs take blood meals and the bites cause hypersensitive reactions. Biological control of bedbugs in Canada has not been attempted and there are no reports of attempts elsewhere.

TICKS

In urban environments ticks could be a problem in nature preserves, parks, and recreational areas. People are seldom infested with large numbers of ticks. Ticks have become a problem of concern because of recent problems with Lyme disease, a disease caused by a spirochete, *Borrelia burgdorferi* Johnson et al., which is transmitted by a tick, *Ixodes dammini* Spielman et al. Other species of ixodid ticks have been incriminated as transmitters of Lyme disease, and some of these species are found in Canada. In Canada eight species of ticks are implicated with 10 and possibly 17 diseases of man and animals (Gregson 1964). Davis (1986) and Van Driesche (1990) have identified an encyrtid, *Ixodiphagus hookeri* (Howard), as a parasite of ticks. Van Driesche (1990) has begun colonization of the parasite and a release is planned in Massachusetts in 1990. Results of this release should be monitored for possible application in Canada. Biological control of ticks should be of high priority for research in Canada because they are potential vectors of diseases and they inhabit recreational areas frequented by urban populations, where chemical controls are not desirable.

CLUSTER FLIES

The cluster fly, *Pollenia rudis* (F.), is possibly second in importance to the housefly as a non-bloodsucking fly pest in Canada. Eggs are laid in cracks in the soil. The eggs hatch and larvae invade earthworms where they develop parasitically for about 2-3 weeks, following which they leave their host and pupate in the soil. There are 2-4 generations per year. In urban situations they are most troublesome in the fall, when they enter buildings to hibernate, accumulating in clusters in such places as attics, closets, hollow walls, and on windows, and in the spring, when they come out of hibernation. Although cluster flies are not of direct public health importance, they constitute a real nuisance, particularly during fall and spring in homes, hospitals, schools, and other public buildings. To date there is no record of attempts to develop biological control agents against the cluster fly. Since part of the cluster fly life cycle is parasitic on the earthworm, biological control may have to be directed at the egg, pupa, or adult stages. Identifying enemies of this pest should be the first step in biological control.

LICE

Human lice are obligate bloodsucking ectoparasites of which three species are recognized: the crab louse, *Pthirus pubis* L., the head louse, *Pediculus capitis* DeGeer, and the body louse, *Pediculus humanus* L. Of the three species, the head louse is the most serious problem in Canada, particularly among school children. There are no reports of biological control of human lice in Canada.

FLEAS

In the urban and domestic environment, the most common fleas are the dog flea, *Ctenocephalides canis* Curtis, the cat flea, *Ctenocephalides felis* (Bouché) and the human flea, *Pulex irritans* L. Both sexes of all three species can bite humans. People who keep pets are prone to flea bites. Fleas are obnoxious not only because of their bites, but because they are potential transmitters of diseases. In Canada, there is no record of any attempts to develop biological control methods for fleas. However, tests in the U.S.S.R. showed that *B.t. thuringiensis* caused mortalities between 69 and 100% in larvae and adults of the plague flea, *Xenopsylla cheopis* Rothschild (Prokop'ev et al. 1976, Nel'zina et al. 1978, Ershova et al. 1980). In another report, *Metarrhizium anisopliae* (Metsch.) and *Beauveria bassiana* (Balsamo) proved to be effective to varying degrees against larvae and adults of the rat flea, *Nosopsyllus fasciatus* Bosc. With the trend to increased urbanization in Canada and the unpopularity of pesticides in dwellings, there is a definite need for research into biological control of fleas.

CERATOPOGONIDS

Ceratopogonids, also called biting midges, no-see-ums, sandflies, and punkies, are the smallest biting flies. They breed in moist situations such as margins of lakes, ponds, swamps, rivers, and creeks, habitats which often occur in nature preserves and recreation areas within or near urban developments; thus, ceratopogonids could be a serious problem. There are no reports in Canada of potential biological control agents for ceratopogonids. Garcia et al. (1980) and Kelson et al. (1980) from the U.S.A. reported that *B.t. israelensis* was only slightly effective against *Culicoides* larvae. Knight (1980) found that some ceratopogonid larvae were susceptible to the fungus *C. clavosporum.* Chiu (1977) in China found an endoparasitic ciliate, *Blantidium* sp., and a mermithid nematode in *Culicoides riethi* Kieffer. The nematode caused ovarian degeneration and sterilization in adults. With the greater demand for recreational areas in urban environments, particularly those near lakes, rivers, streams, and swamps where chemical control is not popular, more research on biological methods is suggested. An inventory of naturally occurring enemies of ceratopogonids would be an appropriate place to start.

TABANIDS

Tabanids is a collective name for horse flies and deer flies (Tabanidae), which can be sporadic pests in urban environments. They are large insects and are active during daylight hours when the weather is warm. Females only seek blood and they are easily interrupted while feeding, which could result in the same female taking several bites to obtain a complete blood meal. In Canada, there are no reports of bacterial, fungal, or microsporidian pathogens from tabanids. Shamsuddin (1966) reported parasitism between 16 and 37% of larvae of *Chrysops furcatus* Walker by a nematode, *Bathymermis* sp., in central Alberta. The same nematode also infected *Chrysops mitis* Osten Sacken when the larvae were maintained in infected soil. Adults of this nematode could not be reared and therefore this nematode could not be cultured in the laboratory. James (1951) reported nematode parasitism in larvae of two *Tabanus* sp. collected at Churchill, Manitoba. *Diglochis occidentalis* (Ashmead), a chalcidoid, appears to be the most widespread enemy of pupae of several species of tabanids. It was recorded from *Chrysops aestuans* Wulp, *C. mitis*, *C. excitans* Walker, and *Tabanus* sp. by Cameron (1926) and Miller (1951). The bionomics of this parasite are not well documented. Cameron (1926) reported the presence of a scelionid parasite, *Telenomus emersoni* Girault, on an egg mass of *C. aestuans* (= *C. moerens* Walk.) and *C. mitis.* The tipulid *Prionocera dimidiata* (Loew) is an aggressive predator on larvae of *Chrysops* sp. larvae (Miller 1951). Predation by *Tabanus* sp. on *Chrysops* larvae has been recorded. Both predation and cannibalism could be important factors in regulating *Chrysops* sp. populations. An increase in use of recreation areas associated with wetlands may require exploration of biological control methods for these pests.

FOOD PRODUCT PESTS

To date there are no known effective biological agents for control of pests affecting food products in the home. Addition of biological control agents to food products may not be acceptable and perhaps is the reason for the absence of research in this area. Modern processing, packaging, and storage of food products reduce the need for control of stored food products.

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SESSION 2: POSTER ABSTRACTS

EFFECT OF AN ECTOMYCORRHIZAL FUNGUS, *LACCARIA LACCATA*, ON *FUSARIUM* DAMPING-OFF IN *PINUS BANKSIANA* SEEDLINGS

P. Chakravarty and S.F. Hwang, Alberta Environmental Centre, Vegreville, Alberta

Damping-off caused by *Fusarium oxysporum* Schlecht. in *Pinus banksiana* Lamb. was reduced significantly when inoculated with an ectomycorrhizal fungus, *Laccaria laccata* (Scop. ex Fr.) Berk and Br. In paired culture, growth of *F. oxysporum* was significantly reduced by *L. laccata*. The number of colony forming units of *F. oxysporum* was reduced significantly in the rhizosphere of *P. banksiana* seedlings when inoculated with *L. laccata*. Spore germination and germ tube length of *F. oxysporum* was inhibited strongly by culture filtrate of *L. laccata* and root exudate of *P. banksiana* inoculated with *L. laccata*. Mycorrhizal seedlings had significantly higher amount of total phenols than nonmycorrhizal ones.

CROSS PROTECTION INCREASES YIELDS FROM *FUSARIUM* CROWN AND ROOT ROT INFECTED TOMATO PLANTS GROWN IN SAWDUST CULTURE

R.J. Copeman[1], G.W. Eaton[1], and B.E. Mauza[2]. [1]Plant Science Department, University of British Columbia, Vancouver; [2]British Columbia Ministry of Agriculture and Fisheries, Abbotsford, British Columbia

Tomato ("Dombito") seeds or seedlings were treated with a mixture of three, cross protecting *Fusarium* strains (CPS) prior to deliberate or natural inoculation with *Fusarium oxysporum* Schlecht. f. sp. *radicis-lycopersici* Jarvis and Shoemaker (FORL) and the yields from individual plants determined. The CPS-treated (at 9 days), pathogen-inoculated plants (at 26 days) had significantly increased mean yields (35%) over a 20-week harvest period compared to pathogen-inoculated but unprotected controls. A second CPS treatment at 58 days did not cause any further increase in yield. CPS-treated plants not inoculated with FORL had mean yields comparable to the unprotected, healthy controls. Plants grown from CPS-treated seeds in commercial greenhouses having severe *Fusarium* crown and root rot problems had increased yields of 18% and 22% compared to non-treated controls. A second CPS treatment at transplanting into rockwool blocks (11 to 15 days) did not increase yields further. Increased yields were due to significant increases in the number of fruits per plant harvested and to a selective increase in the percentage of fruits grading into the extra large category. Commercial application of these cross protecting strains is compatible with current grower practice.

FEASIBILITY OF PREDATOR AUGMENTATION TO CONTROL PEAR PSYLLA IN OKANAGAN PEAR ORCHARDS

L. Edwards, D.J. Lactin, and R. Powlowski, Integrated Crop Management Inc., Box 164, Okanagan Centre, British Columbia

Many Okanagan populations of the pear psylla, *Cacopsylla (=Psylla) pyricola* (Foerster), are resistant to all pesticides registered for their control in Canada. Enlightened use of pesticides allows predator complexes to develop; these generally control psylla. Research was initiated in 1990 to evaluate the feasibility of augmenting predator populations to improve psylla control by this complex. Five predator species were tested: *Campyloma verbasci* (Myer) (Miridae), *Chrysoperla carnea* Stephens (Chrysopidae), *Deraeocoris brevis* Knight (Miridae), *Forficula auricularia* L. (Forficulidae), and *Formica neoclara* Emery (Formicidae). Preliminary results indicate that all show promise.

THE ROLE OF SYSTEMATICS AND THE BENEFICIAL INSECTS PROJECT OF BIOSYSTEMATICS RESEARCH CENTRE IN BIOLOGICAL CONTROL

G.A.P. Gibson and M.J. Sarazin, Biosystematics Research Centre, Agriculture Canada, K.W. Neatby Building, Ottawa, Ontario

The Beneficial Insects Project of the Biosystematics Research Centre (BRC) is composed of a research unit of 10 taxonomists and a biocontrol service unit of two specialists. The taxonomic unit originates, interprets, and transfers systematic knowledge in groups of parasitic and predacious insects necessary for biological control specialists to discover, assess, and manage native and foreign beneficial insects for natural control of insect pests. The biocontrol services unit provides importation, quarantine and rearing services, as well as liaison between Canadian biocontrol specialists and BRC taxonomists and annual information summaries of biocontrol in Canada. The poster summarizes the need for sound systematic research in biological control, the research expertise of the Beneficial Insect Project, and types of technology transfer provided by both the research and biocontrol units. A project proposal is described to develop a micro-computer based beneficial insect parasite database. The database would permit biocontrol specialists and other economic entomologists to quickly and easily retrieve information concerning the nomenclature, distribution and host-parasite relationships of North American parasitic Hymenoptera and tachinid flies.

CONTROL OF ST. JOHN'S WORT (*HYPERICUM PERFORATUM*) WITH A HOST-SPECIFIC *COLLETOTRICHUM GLOEOSPORIOIDES*

K.I.N. Jensen and P.D. Hildebrand, Agriculture Canada Research Station, Kentville, Nova Scotia

A widespread, endemic, host-specific *Colletotrichum gloeosporioides* appears to give a high degree of St. John's wort control in a number of habitats in Nova Scotia, including lowbush blueberry fields. Conidia are readily produced in culture and when applied as foliar sprays containing 10^6 conidia/mL, these sprays gave excellent control of the weed in all stages of growth under both field and controlled environment conditions. The pathogen also occurs on native *H. canadense*, but in host range tests it did not infect any of 21 crops tested, except wound-inoculated tomato fruit, nor was there evidence of latent infection in tolerant species. Optimum conditions for infection and disease development were determined.

POTENTIAL OF *BACILLUS SUBTILIS* TO CONTROL SEEDLING BLIGHT OF CANOLA CAUSED BY RHIZOCTONIA SOLANI

P.D. Kharbanda, Alberta Environmental Centre, Vegreville, Alberta

Effectiveness of *Bacillus subtilis* and *Gliocladium virens* to control seedling blight of canola was evaluated in laboratory and growth chamber tests. In a petri-plate test, seed treated with either *B. subtilis* (Quantum 4000®, @15 gm/kg seed) or a fungicide, iprodione (Rovral ST®, @30 g/kg seed) inhibited mycelial growth of *Rhizoctonia solani* equally well, whereas *G. virens* treatment was ineffective. In growth chamber studies, *B. subtilis* seed treatment did not control seedling blight in *Rhizoctonia* infested soil; however, in combination with a fungicidal formulation, carbathiin + thiram (Vitaflo 280®, 3 mL/kg seed), it was quite effective and controlled the disease significantly better than by the carbathiin + thiram treatment alone. Percent healthy seedlings due to different treatments, 7 and 15 days after seeding respectively, were: *B. subtilis*, 4 and 1; carbathiin + thiram, 38 and 10; *B. subtilis* + carbathiin + thiram, 60 and 24; no treatment, 1 and 0. The results reveal potential usefulness of *B. subtilis* as a biocontrol agent against seedling blight of canola.

DETERMINATION OF PLOIDY STATUS IN GRASS CARP *(CTENOPHARYNGODON IDELLA)*

Marlene Lefebvre, Maria Morwood-Clark, and Kevin Smiley, Alberta Environmental Centre, Vegreville, Alberta

The production of triploid grass carp may be a useful method for biological control of aquatic weeds in the irrigation canals of southern Alberta. These fish are very adaptable and have a high tolerance to environmental changes. Of primary concern is the potential naturalization of grass carp to the detriment of native fish and plants. Therefore, efforts have been made to create a non-reproducing population of carp. This is accomplished by the pressure shocking of fertilized eggs to produce triploid populations. The induction of triploidy in fish is rarely 100% successful; therefore, screening techniques are required to identify triploid individuals before releasing them into the environment. A Coulter channelyzer was used to measure erythrocyte nuclear volume because cell and nuclear size increase in proportion with an increase in ploidy. Chromosome analysis was then performed on blood leukocytes to further confirm the ploidy status. Haematological findings of erythrocyte mean nuclear volumes and chromosome analysis of various types of ploidy will be illustrated in this poster.

LOSS OF VIABILITY OF SPORES OF *COLLETOTRICHUM GLOEOSPORIOIDES*

L.E. Lillie[1], N.J. Temple[1], R. Varma[1], M. Neuwirth[1], and R. Carmichael[2]. [1]Alberta Environmental Centre, Vegreville, Alberta; [2]Philom Bios, Edmonton

Concentrated suspensions (144 $mg{\cdot}mL^{-1}$) of *Colletotrichum gloeosporioides* (CG) lose viability in ≈2 h whereas dilute suspensions (0.144 mg mL^{-1}) retain viability over 24 h. The cause of this was investigated. Concentrated suspensions of CG lose oxygen rapidly (≈3 min) whereas dilute suspensions lose it slowly (≈8 h). That this is a major determinant of viability loss was indicated by findings that gassing CG suspensions with air retards loss whereas gassing with nitrogen accelerates it.

Concentrated spore suspensions of CG were incubated for 2 h and studied by electron microscopy. The spores appear dead rather than dormant. Supernatant prepared from concentrated spore suspension (137 $mg \cdot mL^{-1}$) was found to inhibit CG growth on plates. The factor responsible is present immediately spores are suspended and its effects can be overcome by ten-fold dilution. The substance may be an autoinhibitor.

REGISTRATION REQUIREMENTS FOR BIOHERBICIDES: ENVIRONMENTAL TOXICOLOGY AND FOOD RESIDUE OF *COLLETOTRICHUM GLOEOSPORIOIDES* F. SP. *MALVAE* ON CROP PLANTS

R.M.D. Makowski and K. Mortensen, Agriculture Canada Research Station, Regina, Saskatchewan

As part of the development and testing of registration protocols, the effect on yield and development of cultivars of wheat, flax, lentil, canola, mustard, sunflower, safflower, and sugar beet as well as latency of *Colletotrichum gloeosporioides* f. sp. *malvae* (*C.g.m.*), a bioherbicide for round-leaved mallow, was examined under controlled and field conditions. *C.g.m.* was isolated from all crop cultivars tested under controlled conditions; however, recovery decreased with time of isolation. Except for safflower, *C.g.m.* was recovered from very few field plots, only in trace amounts from leaf material, and only at the two week isolation. There was no significant reduction in biomass for any crop, except for one cultivar of safflower, when treated with *C.g.m.* under controlled or field conditions. *C.g.m.* was not recovered from seed from field treated plots of any of the crops tested.

INFLUENCE OF SOIL MOISTURE ON LARVAL SURVIVAL AND DEVELOPMENT OF *APHTHONA NIGRISCUTIS*, A BIOLOGICAL CONTROL AGENT FOR LEAFY SPURGE

A.S. McClay and R.B. Hughes, Alberta Environmental Centre, Vegreville.

The performance of the root-feeding flea-beetle *Aphthona nigriscutis* Foudras (Coleoptera: Chrysomelidae) as a biocontrol agent for leafy spurge in Canada depends strongly on microhabitat factors. In elevated, dry, exposed sites it has been very successful, while in depressed, moist and sheltered sites it has little impact. We conducted a greenhouse study to determine if soil moisture levels were responsible for these differences. Leafy spurge plants in 15-cm pots were maintained under watering regimes of 100, 200 or 300 mL water/pot/day. At the lowest watering rate plants were often wilted, while at the highest rate the soil was maintained at field capacity. Plants were inoculated with 60 newly-hatched *A. nigriscutis* larvae over a 48-day period. Total numbers of larvae surviving 39 days after the end of the inoculation period decreased slightly with increasing watering. The numbers of larvae reaching the third (overwintering) instar decreased strongly with increasing watering. High soil moisture may thus reduce larval survival and overwintering success. This may contribute to the observed variation in effectiveness of *A. nigriscutis* in the field.

HEALTH AND SAFETY TESTING OF NATURALLY OCCURRING MICROBIAL PEST CONTROL AGENTS

W.J. Murray, Health Protection Branch, Health and Welfare Canada, Ottawa, Ontario

Microbial pest control agents are typically naturally occurring and are widely viewed as more attractive than chemical pesticides. The safety of such agents, however, must be established through the development of appropriate supporting data. Recognizing that these agents are fundamentally different from conventional chemical pesticides, the Health Protection Branch has endeavoured to develop a standardized approach to safety testing in the form of regulatory guidelines. The initial endpoints of concern in the mammalian system include infectivity, toxicity, primary eye and dermal irritation and hypersensitivity. The types of studies required to address these endpoints have been identified; however, no detail is provided on specific protocols. Protocol requirements need to be flexible in order to adapt to changes in technology and to the widely different organisms under development. It may be possible to obtain waivers for certain of the identified endpoints on provision of an acceptable scientific rationale. In evaluating health and safety, all available information is considered. Overall, a qualitative approach to risk assessment is taken. As new microbial pest control agents are identified and the relevant supporting data developed, frequent interaction between regulatory personnel and petitioners is strongly recommended. The present regulatory guidelines are expected to evolve as technology develops and experience is gained by both industry and regulatory officials in assessing the health and safety of microbial pest control products.

EFFECT OF CHEMICAL AND CULTURAL CONTROL METHODS ON DAMSEL BUGS IN CREEPING RED FESCUE GROWN FOR SEED

M.S. Okuda, Alberta Agriculture, Olds, Alberta

The damsel bugs, *Nabis alternatus* Parshley and *Nabicula americolimbatus* (Carayon), are plant bug predators found in creeping red fescue fields in the Peace River Region of Alberta. Deltamethrin applied to fescue in the shot blade stage caused a significant reduction in the number of damsel bugs up to 52 days post-treatment. Spring mowing and mowing combined with straw removal also had an impact on the damsel bug population.

DIAPAUSE AND OVERWINTERING OF *MICROPLITIS MEDIATOR*, A EUROPEAN BRACONID PARASITE OF NOCTUIDAE

K.A. Pivnick, Agriculture Canada, Saskatoon, Saskatchewan

A colony of *Microplitis mediator* originally collected in Switzerland is being investigated as a possible biological control agent for bertha armyworm. Therefore, its potential to survive prairie winters was evaluated. Pupae entered diapause at 16°C, 12:12 (100%) or 14:10 (99%) but not at 16°C 16:8 (0%) or 21°C 16:8. Pupation takes place primarily in the leaf litter but some parasites pupate on the plant (canola) upon which their hosts live. Of diapausing parasites, 100% pupated off the plants while only 74-84% did so under non-diapausing conditions. Diapausing pupae survived up to 24 weeks at −7°C (>90% survival), up to 5 weeks at −16°C (80%), and barely 3 weeks at −21°C (15%). In a field experiment over the 1989–90 winter, 70% of diapausing pupae survived. Considering their coldhardiness and sites of pupation, snow cover would be crucial to survival but they appear to be reasonably well adapted to survive prairie winters.

OCCUPATIONAL AND BYSTANDER EXPOSURE TO MICROBIAL PESTICIDES

R.A. Raphael[1], L. Ritter[1], P. Curry[1], D. Somers[1], S.A. Sattar[1], and V.S. Springthorpe[2]. [1]Health Protection Branch, Health and Welfare Canada, Ottawa, Ontario; [2]Faculty of Health Sciences, University of Ottawa, Ottawa, Ontario

Microbial pesticides are currently used in Canada for the control of silviculture and agricultural pests. The Health Protection Branch performs a human health and safety assessment of pesticides proposed for registration or subject to re-evaluation in Canada. Guidelines have been developed for the safety testing requirements for microbial pest control agents. Humans may have contact with these pesticides through occupational and bystander exposure in treated areas or through food and water. The classical routes of exposure, considered to be important in the transmission of infectious disease, also apply to microbial pesticides. For occupational and bystander exposure, the identified routes of exposure may be direct inhalation and skin contact to transfer of the agent via hands to mouth, nose, eyes or other mucosal surfaces and indirect transfer from contaminated clothing or other surfaces. The many factors to be considered in quantitive and or qualitative assessment of occupational and bystander exposure include adequate study design, appropriate sampling and detection methodology as well as reliable estimates of background exposure levels of populations to naturally occurring microbial pest control agents.

IMPACT OF CHEMICAL AND BIOLOGICAL PESTICIDES ON MORTALITY AND BEHAVIOR OF *COLEOMEGILLA MACULATA LENGI*

Caroline Roger[1], Charles Vincent[2], and Daniel Coderre[1]. [1]Dépt. Sci. Biol. Université du Québec à Montréal, Montréal, Québec; [2] Agriculture Canada Res. Station, St-Jean-sur-Richelieu, Québec

Indiscriminate use of pesticides may counteract the efficiency of biocontrol agents. The sole evaluation of pesticide toxicity (direct mortality) does not adequately describe the full impact of pesticides on arthropod natural enemies. The assessment of the direct impact of pesticides in laboratory and field conditions may be biased due to a temporary inactivity following the treatment, hereafter named "apparent mortality". The goals of this study were to evaluate: 1 - the impact of four chemical pesticides (malathion, carbaryl, cypermethrin and benlate) and two neem (*Azadirachta indica* Juss.) formulations on the coccinellid predator *Coleomegilla maculata lengi* Timberlake (Coleoptera: Coccinellidae). The toxicity was evaluated in laboratory with topical application on the abdominal thorax of adult ladybeetles. Mortality was assessed 15 min, 1, 2, 4, 24, 48 and 72 h after application. Malathion, carbaryl and cymbush caused at least 75% mortality while benlate, water extracts of neem seeds and neem oil had no significant effect on mortality. From one to eight hours after treatment, up to 40% mortality was observed with benlate. For carbaryl, neem seeds and oil, apparent mortality peaked respectively at 48, 8 and 1 hr after treatment. Misevaluation of mortality may have serious logistic consequences in a context where a pesticide is expected to function optimally. The implications of our findings are discussed in the context of Integrated Pest Management programs.

USE OF PLANT CHEMICALS TO MANIPULATE ATTACK BY THE PARASITIC FLY *CYZENIS ALBICANS* ON THE WINTER MOTH

J. Roland[1], K.E. Denford[1], W.G. Evans[1], and J.H. Myers[2]. [1]University of Alberta, Edmonton; [2]University of British Columbia, Vancouver, British Columbia

The parasitic fly *Cyzenis albicans* (Tachinidae) attacks its host the winter moth, *Operophtera brumata* (Geometridae), by ovipositing on foliage damaged by the feeding host larvae. The pattern of this attack suggests that flies are responding to chemical released by the damaged plant, and lay most eggs on the most heavily damaged plants. Although this pattern is observed on some plant species such as oak, it is absent on others such as apple, suggesting that the latter lacks the chemical cue involved. By applying oak leaf extracts to apply trees, we were able to increase the level of parasitism of winter moth in an apple orchard. These results suggest that plant compounds could be used to enhance the probability of success in attempts at biological control. Current studies involve the identification of the specific chemical(s) involved.

ISOZYME PATTERNS OF *CHONDROSTEREUM PURPUREUM* BY VERTICAL POLYACRYLAMIDE GEL ELECTROPHORESIS

S.F. Shamoun, D.C. Thom, R.E. Wall, and A.K.M. Ekramoddoullah, Forestry Canada, Pacific Forestry Centre, 506 West Burnside Road, Victoria, British Columbia

The biochemical characterization of 17 isolates of *Chondrostereum purpureum* (Fr.) Pouzar, a potential forest mycoherbicide, was attempted by detection of isozymes using polyacrylamide gel electrophoresis (P.A.G.E.). Isolates were collected from different plant hosts across Canada and grown for two weeks under controlled conditions. The mycelium for each isolate was collected, freeze dried and homogenized in cold acetone. For this preparation, a protein extract was derived and its protein concentration determined by the Bradford standard protein assay. The banding patterns of general proteins and 13 enzyme systems were visually observed by vertical P.A.G.E. The eight enzyme systems which produced positive activities were once again subject to P.A.G.E., but using *C. purpureum* protein samples standardized to 150 µg protein/well). Although the relative migrations of bands are generally similar between isolates for a given enzyme system, they varied noticeably in their intensities (especially acid phosphatase, beta-esterase, peroxidase, beta-glycosidase and polyphenoloxidase). Results suggest the possibility of characterizing activity patterns for each isolate but must first be correlated with pathogenicity studies before the virulence of a given strain can be quantified using biochemical assays.

INDIGENOUS MORTALITY AGENTS HINDER BIOLOGICAL CONTROL OF THE APPLE ERMINE MOTH, *YPONOMEUTA MALINELLUS*, IN SOUTHWESTERN BRITISH COLUMBIA

R.B. Smith, Vedalia Biological Research, R.R. 2, Porlier Pass Dr., Galiano, British Columbia

Since 1987, *Ageniaspis fuscicollis* (Dalm.) Thoms. (Encyrtidae), an egg-larval parasitoid, has been repeatedly introduced into southwestern British Columbia as a biological control agent for the apple ermine moth, *Yponomeuta malinellus* Zeller (Yponomeutidae). However, establishment of *A. fuscicollis* has been poor and spread beyond release sites has been negligible. Data are presented implicating indigenous mortality agents as responsible for the poor establishment of *A. fuscicollis*.

The predatory mite, *Balaustium* sp., (Erythraeidae) causes high mortality of egg masses. This mite has no preference for any particular age of egg mass: egg masses laid earlier in the season are more likely to be eaten by *Balaustium* than egg masses laid later in the season, simply due to the longer time they are exposed to predation. *A. fuscicollis* emerges early in the oviposition period of the apple ermine moth and is only able to parasitise those egg masses laid early. Therefore, parasitised egg masses are subject to heavy predation.

In addition, mortality of late instar larvae of the Apple Ermine Moth by a variety of generalist predators, particularly birds, is high. Experimental evidence is presented that suggests parasitised larvae are less likely to escape larval predation than are unparasitised ones, further decreasing the likelihood that *A. fuscicollis* will become a successful biological control agent of the apple ermine moth in British Columbia.

BIOLOGICAL CONTROL OF FOREST INSECT PESTS USING TRICHOGRAMMID EGG PARASITOIDS

S.M. Smith, E. Forsse, R. Bourchier, Z. Wang, N. Maheswaran, and K. Strom, Faculty of Forestry, University of Toronto, Toronto, Ontario

Egg parasitoids of the genus *Trichogramma* are being investigated for their use against forest insect pests such as the spruce budworm, *Choristoneura fumiferana* (Clemens), the forest tent caterpillar, *Malacosoma disstria* Hübner, and the spruce budmoth, *Zeiraphera canadensis* Mut. & Free. The propensity, timing and temperature threshold for flight by *T. minutum* held under varying environmental conditions has been established in the laboratory. These studies are now being linked to parasitization levels under semi-field conditions. Shifts in fecundity, longevity, and flight of parasitoids reared continuously at high laboratory temperatures (25°C) has been related to changes in biochemical patterns (isozymes) in order to predict the efficiency of parasitoids released in the field. Biological and biochemical characterizations of parasitoids collected from within and between different field sites show a high degree of variability, suggesting that only small localized collections of *Trichogramma* need to be made when establishing colonies for mass-rearing and release. Preliminary studies have also been initiated to determine the susceptible period for parasitization by *Trichogramma* on eggs of the forest tent caterpillar and the spruce budmoth. This will enable release programs to be developed in the future against these forest pests.

BIOLOGICAL CONTROL OF GREENHOUSE PESTS IN ALBERTA — A STATUS REPORT

M.Y. Steiner, Alberta Environmental Centre, Vegreville, Alberta

Research conducted at the Alberta Environmental Centre on integrated pest management of greenhouse pests has focused on two major pests, the western flower thrips, *Frankliniella occidentalis* (Pergande), and the sweet potato whitefly, *Bemisia tabaci* (Genn.). Progress has been made in evaluating the predatory mite *Amblyseius cucumeris* (Oudemans) and the pirate bug *Orius tristicolor* White for thrips control in pepper and cucumber crops, in establishing distribution of pest and predators in each crop, and sampling procedures. The aphelinid wasp *Encarsia formosa* Gahan is being evaluated for efficacy against sweet potato whitefly on poinsettia. This is posing difficulties because of limited information on sampling techniques, varietal differences, and production practices.

COLLECTION AND SCREENING OF PLANT PATHOGENS FOR POTENTIAL MYCOHERBICIDES IN ALBERTA

Rina Varma, Alberta Environmental Centre, Vegreville, Alberta

Diseased weeds were collected in summer of 1988 and 1989 from central and southern Alberta. From 137 specimens, 394 fungal and bacterial isolates were purified and stored in culture tubes at 4°C. These isolates were tested for pathogenicity, efficacy and host specificity in controlled environment chambers. Fifty-nine isolates from 30 weed species proved to be parasitic to their respective hosts according to Koch's postulates. These isolates were assessed for their control potentials. This screening resulted in 25 isolates giving moderate to excellent control of their respective host weeds. Preliminary host specificity tests were conducted with these 25 isolates against wheat, barley, canola, flax, safflower, alfalfa, pea, lettuce and tomato. Results were very encouraging as none of these crop species were affected by the candidate mycoherbicides used. Further host specificity tests on plant species closely related to the target weeds will be conducted. The final stage of this research will be to evaluate the efficacy of candidate mycoherbicides in the field.

BIOLOGICAL CONTROL OF PHYTOPHAGOUS MITES AND METAPOPULATION STRUCTURE: DOES NUMBER OF POPULATIONS AFFECT DYNAMICS?

Sandra J. Walde, Department of Biology, Dalhousie University, Halifax, Nova Scotia

A problem in the theory of biological control has been to identify the spatial scale at which a natural enemy-pest interaction persists or is stable. One alternative to the classical theory which postulates stable interactions with in populations is a metapopulation structure where local populations may be unstable, but the ensemble persists via migration. This type of interaction has frequently been postulated for phytophagous-predacious mite systems, based on laboratory and modelling studies. Here I use

European red mite, *Panonychus ulmi*, and its predator *Typhlodromus pyri* to determine if this mechanism is relevant to field populations. By establishing an orchard with trees in groups of 1, 4 and 16, I tested the hypotheses that increasing the number of interacting populations increases persistence, and lowers temporal variability and average density. I found that the presence of neighbouring populations did affect local population dynamics. Populations in the largest groups did tend to persist longer but, contrary to expectations, this did not lead to better control. In fact, trees in the largest groups had both higher average densities and higher temporal variability of the pest. The physical mechanism producing this effect was likely a passive trapping effect by the group of trees. It was concluded that (1) among-population interactions are important in determining the dynamics of these phytophagous mites in the field, and (2) that a mechanism that increases persistence may not lead to lower temporal variability, and that the latter may be more important in biological control.

SESSION 3: CURRENT ISSUES

Biological Control: the Old and the New

J.K. Waage
International Institute of Biological Control, Silwood Park, Buckhurst Road, Ascot, Berks. SL5 7TA, UK

ABSTRACT *Biological control activities have increased rapidly in recent years, both in developed and developing countries, largely as a result of public concern over the environmental and economic costs of chemical pesticides. Trends in biocontrol are examined through examples from IIBC and Canadian projects. The "classical" biocontrol strategy — introduction of exotic natural enemies against exotic pests — will always have a place, but the focus of biocontrol is shifting towards natural enemy conservation and biopesticides. When key natural enemies of pests are identified, agricultural practices can be modified to enhance their impact. The development of effective delivery systems is an important focus in biopesticide research. Canadian programs in classical biological control can be strengthened by careful selection of target pests, the use of ecological studies to select promising agents, involvement of Canadian scientists in overseas exploration, and a strong commitment to implementation.*

INTRODUCTION

In this paper, I have been asked to contrast the old and the new in biological control, and thereby to suggest where biocontrol is going and what it needs now to get there. To this ambitious task I will try to bring two modest perspectives, based on my experiences at the International Institute of Biological Control (IIBC). The first involves the global trends apparent in biological control in both developed and developing countries. The second is the experience of our classical biological control activities on behalf of Canada, a subject with a long and successful history.

With respect to the "old" of biological control, IIBC has a reasonable claim to speak with some authority. Still known to many as the Commonwealth Institute of Biological Control or CIBC, the institute began in 1927 from laboratories at Farnham House in England. Since then, IIBC has provided the only truly international service in biological control. Today, as a fully international organization, IIBC undertakes over 40 programs in biological control annually, on behalf of or with about 45 countries worldwide. As a non-profit organization, IIBC's continuation depends on the global demand for biological control and its own ability to attract funding for innovative research programs.

During this long history, Canada has figured significantly in IIBC's activities, providing it with some of its most distinguished Directors, scientists and projects. Canada was host to IIBC for part of its history, and Canadian aid built its overseas stations in Trinidad and Kenya.

IIBC's development depends on perceiving changing directions and needs in biological control and responding to them. Therefore, a view of how we are changing will, I hope, serve as a mirror on the world situation.

One of the most striking trends in biological control here and elsewhere is the growth of its activities in recent years. Research in the university and commercial sector is increasing, while in the public sector new institutions for biological control are being created at an impressive rate. In the past year, for instance, progress has been made in the development of a new national institute for biological control within the USDA, and a new European institute, to be called the Centre International de la Lutte Biologique Agropolis and based in Montpellier, France.

In industrialized countries, recent institutional development in biological control has often involved a reorganization of existing resources in agricultural research under new headings, sometimes without substantial new investment. In developing countries, by contrast, efforts at institution building has been accompanied by substantial new financial investment from development assistance agencies. For instance, a US $3.5 million centre for biological control in Africa was opened in Benin in 1988, while 1989 saw the opening of the Centre for Biological Control in Central America in Honduras.

Why is biological control on the upswing? Does this result from new technical advances which are generating new interest? No, I would suggest rather the opposite. Public interest in biological control is growing as a result of concern about pesticides and the environment, and this is generating resources for new technical advances.

Let me illustrate this process with three recent examples. Restrictions on chemical pesticide use in Canadian forests have generated considerable renewed interest and funding for work on *Trichogramma* spp. and *Bacillus thuringiensis* Berliner (*B.t.*). A political decision has created a market which, in turn, has spurred multinationals like CIBA-GEIGY and ICI to invest in basic research on some old products sorely in need of improvement. The possible results, cheaper methods of *Trichogramma* mass production and more virulent and persistent *B.t.* strains, will find useful application far beyond the Canadian forest.

In Indonesia, a presidential decree in 1986 banned 57 broad spectrum pesticides on rice, because they caused resurgence of brown planthopper there. This has not only greatly improved the lot of the Indonesian rice farmer, through a reduction in pesticide costs and higher yields, but it has increased interest in biological control research in universities and government institutes throughout Southeast Asia. Further, it has encouraged development assistance agencies to fund much of this new research, from which further advances in understanding and methods are bound to come.

Finally, concern over the environmental impact of the over US $150 million worth of broad spectrum pesticides used in the recent locust plague has compelled development assistance agencies, which provided about half of this sum, to support investigations into alternatives to chemical pesticides. The United Nations Development Program is sponsoring a major funding program for projects in non-chemical control, while a consortium of four donors, including Canada, are supporting a US $5 million project at IIBC to develop fungal insecticides for locusts and grasshoppers. Even if this research does not lead to a solution for locust control, the development of methods to assay and characterize insect pathogenic fungi, and of techniques for their formulation for use in arid environments, will have valuable spin-offs for biological control of other tropical pests.

CHANGES NORTH AND SOUTH

It is significant from the above examples that the political force which is driving the improvement of biological control is felt both in the developed and developing world. For once in agriculture, the developed world is not well ahead of its developing neighbours in pursuing these new approaches to pest management. While the pressure for change in the North comes from public concern about pesticides, in the South the push is coming as well from a desire to reduce dependence on expensive, imported and often inappropriate chemical pesticide which eats into the foreign exchange budgets of small tropical countries.

But the developing world, despite its enormously rich living resources for biological control, has limited infrastructure and support to undertake the necessary research and development. By virtue of their very specificity, biological control agents developed for temperate pests may not be useful in the control of tropical pest species. The incentive for companies in the North to develop biological control for tropical pests in the South is low - the small market simply does not justify the cost of research and development.

Helping developing countries to achieve their goals in biological control is a growing element of our work at IIBC. Today, over half of our annual project budget is spent on projects for developing countries. This changing situation is even visible in the contribution of the Canadian taxpayer to IIBC's activities. Only a decade ago, Canadian support to IIBC went largely towards the provision of biological control agents for Canadian pests. Today, annual funding from Canada for Canada is actually less than funding from Canadian aid organizations, including CIDA and IDRC, for work on behalf of developing countries.

CHANGING EMPHASIS IN BIOLOGICAL CONTROL

Until recently, the term biological control usually evoked images of the so-called "classical" introduction of exotic agents against exotic pests. This was nowhere more true than in IIBC, where exploration for, and introduction of, exotic natural enemies was our major activity.

Today the situation has shifted dramatically. In 1990, IIBC spent slightly less than 50% of its project funds on classical biological control work, while the rest went to new projects for the development of biological pesticides and the conservation of natural enemies in integrated pest management (IPM) systems.

A global partitioning of biological control activity would be even more skewed. Commercial interest in biopesticides has led to a level of investment which dwarfs that for classical biological control and IPM research. These latter two areas, where profits are not to be made easily, inevitably remain the domain of public sector research and funding. As we shall see, however, without progress in research on conservation and IPM, the value of our enormous investment in biopesticides may be fleeting.

It is my opinion that, while classical biological control will forever find a place in a world where plants and pests are constantly on the move, the next few decades will see the emergence of research into natural enemy conservation, supported by research on biopesticide development, as the main focus of biological control.

Let me now consider briefly the three areas I identified above; conservation, biopesticide development and classical biological control, and where they may be going tomorrow.

CONSERVATION OF NATURAL ENEMIES

On a global scale, the action of natural enemies already present in the crop system must make a far greater contribution to pest management than the — admittedly more spectacular — introduction of classical biological control agents or application of biopesticides. It is ironic, therefore, that so little investment has gone into research on conservation, relative to these other areas.

Conservation of natural enemies is an enormously broad subject, but over the past two decades, research seems to be concentrating into two areas: (1) increasing diversity in modern crop monocultures to meet natural enemy needs and (2) integrating the use of chemical and biological pesticides with the action of natural enemies.

An initial burst of enthusiasm for research into modifying crop environments came in the 1970s from examination of traditional farming practices, particularly intercropping. Many years and much research later, the case for intercropping seems more equivocal (Altieri and Letourneau 1984). Sometimes it improves natural enemy action, sometimes not. It is my impression that this is the likely conclusion of all efforts to improve biological control by gross manipulation of crop structure. A more cost effective and successful approach, which is gaining popularity, would be to first to identify the important natural enemies affecting the pest, and then to investigate their specific needs as a basis for crop modification.

A good recent example of the success of this approach comes from IIBC's Pakistan Station, where research has been under way on the serious homopteran pest of sugar cane, *Pyrilla perpusilla* Walker. Expensive aerial sprays are applied every year for control of this pest in parts of the Sind region. Research on its natural enemies revealed a significant impact of specialized egg parasitoids which increased as the season progressed. Traditional farming practices involve collection and burning of sugar cane "trash" (dead leaves, etc.) after harvest. Examination of trash revealed high densities of *Pyrilla* eggs, heavily parasitized by *Tetrastichus pyrillae* Crawford. The failure of the egg parasitoid to achieve levels of parasitism at the beginning of the growing season sufficient to prevent pest outbreaks appeared, therefore, to be linked to the destruction of parasitoids between seasons by burning of trash. An alternate strategy of piling trash by the field was proposed, and where this is practised now, pest numbers do not reach levels where chemical control is required. Where parasitoid survival is poor between seasons for other reasons, augmentation of parasitoids early in the season can achieve the level of parasitism necessary to prevent pest outbreaks.

The other major area of current research into conservation is in the integration of chemical and biological control. Protocols have been developed for the testing of pesticides on natural enemies in the laboratory, which provides an important baseline for selecting pesticides on the basis of their compatibility with biological control. While it is widely appreciated that effects in the field may be different, work on field effects of pesticides on biological control is still limited, and faces some challenging problems of experimental design and interpretation.

The direction of future research on pesticides and biological control is very much linked to the philosophy of IPM, whereby pesticides are used only when other measures (including natural enemies) will not prevent economically damaging levels of the pest. This means that, ultimately, measurements of natural enemy numbers or impact must be incorporated into spray thresholds or other decision rules for pesticide use. Much more work needs to be done in this area.

Failures to incorporate the natural enemy contribution into spray decisions are already creating problems which may seriously limit our options in future. A case in point is that of the diamondback moth, *Plutella xylostella*, a serious pest of brassicas worldwide. In the tropics, *Plutella* has developed a degree of resistant to all groups of broad spectrum pesticides. It has an effective complex of larval and pupal parasitoids which in some cases can keep pest populations below economic levels. In some cases they cannot, but in most cases, intensive and escalating pesticide usage, in the face of mounting resistance, has eliminated these natural enemies and pest management is at crisis state.

A solution to this crisis emerged a few years back with the introduction of *B.t.* and insect growth regulators (IGRs) into *Plutella* management. The effect was striking. Both products were able to give effective control of the pest without seriously affecting natural enemies, which now cause high levels of parasitism. However, within a few years of their introduction into Southeast Asia, substantial resistance has developed to IGRs, and resistance has even appeared to *B.t.* What happened?

While the elements of integrated pest management had been put in place — the contribution of natural enemies and the use of selective pesticides — the integration had simply not been done. Farmers continued to spray *B.t.* and/or IGRs on a calendar basis, and at a frequency similar to that which they had used with broad spectrum compounds, leading quickly to resistance. This was probably far in excess of what was needed, given the regained contribution of natural enemies. But this contribution had not been quantified and incorporated into decisions about spraying. As a result, the only promising solution to this particular problem is rapidly being lost.

This is one of a number of examples which highlights the importance of natural enemy conservation to the management of pesticide resistance. Increasingly, it is becoming clear that biological control has the potential not only to replace much present use of chemical pesticides, but to prolong as well the life of those chemicals which we will still need into the next century.

BIOLOGICAL PESTICIDES

The addition of insect natural enemies to crops has a long tradition, not the least through the use of species of *Trichogramma*, which continues in tropical and temperate regions. Trends in the use of insect natural enemies today are away from their regular, mass release as "biological pesticides" towards strategic releases of small populations for establishment and reproduction. This cost effective approach requires basic understanding of population dynamics of pest and natural enemy, but holds the promise of being able to regularly "prime" crops with the appropriate natural enemies early in the season to suppress pest population growth.

However, the major developments in adding natural enemies to crops must be in the area of pest pathology, and the development of nematodes and pathogens as biological pesticides. Much has been said at this workshop on the promise of specific pathogens, their development and registration. Therefore, I will only make a few observations.

Development of biopesticides has been steered to date by a range of constraints. Only a small number of pathogens have been found to have a desirable, quick action and a capacity to be reared on cheap artificial media. In the next few decades, improvements in strain selection, and perhaps modification through genetic engineering, and in vitro production of pathogens, have the potential to greatly widen this portfolio of control agents. This can only be achieved through much basic research on the characterization and biology of these organisms.

But even with the pathogens with which we can work today, there is an existing constraint which must be overcome by research. This is in the effective delivery of the pathogen to the pest. While the most sensational developments in this area involve the incorporation of pathogen genes into plants, new formulation and application methods for biopesticides are another promising area for research. Recent work on oil-based fungal formulations for foliar application and methods to deliver pathogens effectively to soil pests represent two exciting directions for research, the latter spurred by increasing restrictions on the use of persistent chemical pesticides for control of pests in soil.

CLASSICAL BIOLOGICAL CONTROL

Let me turn now finally to classical biological control, which is not only our major activity at IIBC, but the one in which we interact most with Canadian scientists.

The introduction of exotic natural enemies for long term suppression of pests has an impressive record. For insects, over 4,000 introductions have been made, leading to about 1,000 establishments in about 1,000 projects. Of these projects, about 25% have led to good control of the pests.

Less effort has been put into weeds, but the resulting level of success is higher, close to 50%. Of course, ratings depend upon what you call success, and I do not wish to labour this point here.

These kinds of statistics are derived from past records of biological control, accumulated on databases such as IIBC's BIOCAT and *Biological Control of Weeds* (Julien 1987). In principle, these data can also be used to contrast the old and new in biological control, to see how we have progressed. In practice, the data available and the many other factors which determine which projects are done do not really permit this, but what analysis has been done, on weeds (Julien et al. 1984), does not show a clear improvement in success over the last century. So much more, then, the challenge for the future.

However, one where important improvement can be identified is in safety. Protocols for safety testing of agents, particularly for weed control, are increasingly followed and agreed internationally. IIBC has just prepared for the FAO a draft of an international code of conduct in the safe use of biological control agents, which will hopefully be ratified by the United Nations in the next year, following expert consultation with Canadian and other practitioners. This code is intended to guide countries and scientists, particularly those new to classical biological control, in proper procedures to ensure that agents for introduction are safe and have been properly quarantined.

Let me return next to the statistics of success given above. Biological control practitioners spend so much of their time convincing authorities of the value of classical biological control that we automatically think of its success rate as impressive. Amongst ourselves, however, we must admit that it should be possible to achieve better than 25–50%. If this represents the old in classical biological control, how do we make the new more successful?

I would suggest three basic areas where attention may be focused in order to improve classical biological control:

1. Selection of target pests Target pests must be selected on the basis of a carefully prepared scientific and economic case, which compares the project losses from the pest with the cost of the biocontrol program, its probability of success, and its projected benefits. In this way, target pests unlikely to be successfully controlled can be weeded out (unless there is a very strong economic case for proceeding). More importantly, projects with a strong economic and scientific justification are more likely to receive the commitment necessary for effective exploration and implementation. All too often in public institutions, classical biological control projects become elements of annual budgets. In such circumstances, poorly justified projects run the risk of arbitrary termination when budgets become tight or their defenders move on to new interests.

2. Exploration for biological control agents There are many opportunities to improve exploration, an area which receives a remarkable range of effort, as I will discuss in more detail below. There is, in my view, a very strong case for ecological research studies, in both the area of origin and introduction, as a basis for successful exploration and selection of agents.

3. Implementation of selected agents Unless the commitment to implementation is strong, programs stand a risk of failure. Exploratory work is expensive, and the agents provided, usually in small numbers, are therefore extremely valuable. All too often, poor facilities or staffing at the receiving end of such shipments wastes this considerable investment.

Many agents are difficult to rear and establish, but it has been shown in Canada and elsewhere that effort in establishment, particularly the number of agents released and the selection and preparation of release sites, improve the chances of establishment and success (Beirne 1980).

EXPLORATION FOR CLASSICAL BIOLOGICAL CONTROL AGENTS

IIBC's major activity on behalf of Canada involves exploration for biological control agents for exotic weed and insect pests. The way in which exploration is carried out is one of the most variable components of classical biological control. Let me contrast two extremes.

Some leading biological control organizations approach exploration as a research program, combining a survey for biological control agents with detailed ecological studies on the pest in its area of origin and intended introduction. Research findings are used to select from amongst the agents discovered.

Other leading organizations focus efforts on short collection trips, from which as many potential agents as possible are brought back for screening and possible release. These organizations may also solicit shipments of agents from private collectors and other institutions. Some preintroductory studies may be done, invariably in the laboratory.

Clearly, the latter approach sacrifices a degree of knowledge of the system for a greater diversity of potential agent species and races. Its practitioners may be of the opinion that classical biological control is too complex an ecological phenomenon to be predictable. Therefore, they gamble on a lucky find, and it may pay off. But there is, I would suggest, a fundamental flaw in this approach.

All classical biological control programs suffer from a lack of financial resources relative to natural enemies. With few exceptions, programs end before all potential agents have been tried. If there is no scientific basis for selection of agents, this must needs be arbitrary. It would seem therefore that any research which would indicate which agents may prove more effective could only increase success.

Further, exploration without research leads invariably to success or failure without understanding. Such work is neither intellectually satisfying to the practitioner nor capable of improving biological control, except by the slow accumulation of precedents.

To be fair, the collection trip approach may reflect some practical constraints. Foreign exploration is expensive and it is often easier for biocontrol programs, particularly those operating from universities, to pay for work at home than abroad. Therefore, there is frequently little choice but to accumulate as much material as possible through quick collection trips for study in the intended country of introduction.

Similarly, it must be said that exploratory research per se does not guarantee successful selection of agents. In programs against North American forest pests, detailed life tables have been made in the area of origin for only two target pests, the larch casebearer, *Coleophora laricella* (Hübner) and the winter moth, *Operophtera brumata* (L.). Neither study identified parasitoids as important factors in depression pest populations in Europe, but in both studies it was, indeed, unimportant European parasitoids that gave effective control in North America. Exploratory programs which focused only on these life table studies might have missed picking the winners. Exploratory research must go beyond simply a measurement of the mortality caused by natural enemies in their area of origin to an understanding of what factors affect their impact there and what may affect their potential impact in a new region. The interaction of biological control agents with other mortalities acting on the pest has, for instance, emerged in recent years as a major factor influencing the success of classical biological control (Waage 1989), and deserves particular consideration in exploratory research.

Those who would see classical biological control as too complex to predict can point to a long history of mathematical modelling of biological control which has been of little practical benefit. However, new approaches to modelling are being tried today which offer more promise. This involves construction of models which use a minimum of variables and focusing on suspected key dynamical elements of the interactions between natural enemies and other factors, the consequences of which may not be intuitively obvious (Murdoch et al. 1987, Godfray and Waage in press). Future development of models to help exploration, whatever their form, must address the fundamental constraint that, to be useful within the time span of a project, they must be easy and quick to build with the minimum of biological information.

IIBC EXPLORATION FOR CANADA

In its programs with Canada, IIBC and its Canadian counterparts are committed to a strong research component to exploration. We feel that research pays off, and recent programs with Canada are showing this. For instance, exploration for biological control agents of the gypsy moth, *Lymantria dispar* (L.), has focused in recent years on the natural enemy complex attacking low density, endemic populations of the pest. In principle, it is these natural enemies which are most valuable in preventing outbreaks.

This research has involved development of the "host exposure" method for sampling natural enemies, and has revealed a rather different complex than is found in gypsy moth outbreaks in Europe. One agent, the tachinid *Ceranthia samarensis* (Villeneuve), appears particularly promising.

The important point here is that gypsy moth has been the subject of almost a century of exploration, mostly of the "collecting trip" kind. Collecting trips, invariably, are constrained to seek and exploit outbreak populations of the pest. Today, despite the introduction of over 50 natural enemy species collected in this manner, gypsy moth is still a serious pest. The establishment by IIBC and Canada of exploratory research on gypsy moth, therefore, seems not only timely but long overdue.

The gypsy moth program represents, sadly, an exception rather than the rule in current exploratory programs for Canadian insect pests. While we have a commitment to appropriate research in all exploration, in some sectors the budget is far too limited and the projects are too numerous to do much else than collect, rear and ship. This is frustrating, and it reflects a continuing problem with Canadian programs which needs urgent attention.

In 1990, IIBC will conduct 15 exploratory programs on behalf of Canada, directed against particular insects and weeds. The effort and resources for each differ considerably. Forestry programs, including gypsy moth, spruce budworm, spruce weevil and eastern budworm, are relatively well supported. Canadian counterparts meet annually to consider IIBC results and, in consultation with IIBC, plan the next year's work. Canadian scientists participate actively in summer research at our station in Delémont, thereby ensuring the intellectual and logistical interchange which is important for success.

Weed projects (leafy spurge, knapweeds, houndstongue and Dalmatian toadflax) are also well supported as a result of the development of a very effective consortium of federal and provincial support and good coordination of a regional effort.

Programs against insect pests of agriculture, by contrast, are poorly funded and in need of coordination. Seven projects — bertha armyworm, wheat midge, apple maggot, apple ermine moth, Russian wheat aphid, blueberry leaf tier and European earwig — share a funding level less than one quarter of that available to the four weed projects. A need to spread this funding geographically between regions and stations ensures that no one project gets sufficient funding. Further, the requirement for regional distribution of projects may lead to the selection of some projects which have limited economic and scientific justification than others, and therefore less commitment in terms of facilities and manpower. All too often, scarce exploratory funds are spent developing promising agents only to find that the effort has been wasted because the Canadian counterpart has left or changed interests. Such has been the fate recently of a very promising project against the antler moth, *Cerapteryx graminis* (L.), in Eastern Canada.

Thus, IIBC programs for Canada present today a broad spectrum of investment. Much pride can be taken in the well supported and coordinated projects. Less well supported projects do Canada no service - they signify potentially wasted investment and heap unnecessary failure on a country with one of the best track records in biological control.

The problem of projects against insect pests of agriculture is not one which can be solved simply by increasing funding for exploration, even if this were possible in the present financial climate. There is a need for organizational as well as financial development. I would suggest three actions for consideration:

1. Prioritize projects — reduce their number. The sheer number of projects against agricultural pests is presently a constraint on the use of limited funds. Their reduction will put more effort on fewer targets and will, I predict, improve the overall rate of success in the long term.

Existing targets should be prioritized, and a few selected on the basis of superior economic and scientific justification. Participants will have to accept that maintaining geographical balance, and hence many small projects, is to no one's long term interest.

With a few well justified programs, it will be possible not only to raise the profile of biological control for agricultural insect pests, but to argue more effectively for the involvement of other organizations (eg. provinces, commodity boards) in their support, in the manner of the Canadian weed programs.

2. Involve Canadian scientists at all stages in the process Crucial to the success of any program operating over such distances is the commitment and communication of all involved. In a human sense, this commitment is generated by a feeling of involvement and responsibility. Accordingly, it is important for Canadian scientists to be involved in the planning of research as well as the actual work in Europe, as is presently done in some forestry projects.

3. Strengthen capacity and commitment for implementation Implementation of biological control requires dedicated facilities and staff over prolonged periods. It cannot be done as an minor element of the research program of a particular scientist, drawing upon environment rooms and technical support on a casual basis. Rather, it needs planning and commitment of resources.

I would stress that these thoughts come from a personal and distant perspective, and no doubt fail to appreciate some of the subtleties of the situation in Canada. They represent my interpretations of problems and suggestions voiced over the years by staff at our Delémont station and counterparts in Canada, and I hope that their presentation here might aid the necessary process towards their solution.

CONCLUDING REMARKS

Biological control is enjoying today a renaissance, after many years in the shadow of a pesticide-dominated crop protection industry.

This brings opportunities and responsibilities. Opportunities in Canada and elsewhere are reflected in an increased investment in biological pesticides, the rapid growth of biological control in sectors like the greenhouse industry, and continued enthusiasm for classical biological control. Conservation of natural enemies is a relatively neglected area which deserves more attention in future, particularly as it will be crucial to the effective use of other forms of biological control in IPM programs.

Canada's long and successful precedent in classical biological control has laid a foundation for these new developments. Its own future depends on maintained investment and, I would suggest, rationalization of that investment to ensure that projects are adequately supported both in their exploratory and implementation stages.

Finally to the responsibility which comes with the opportunity. Given the public's interest in green issues, it is easy today to promote biological control. Best use must be made of such interest, avoiding unrealistic promises and stressing the importance of research to the development of effective new methods. Biological control practitioners must, as well, play a greater role in the safety aspects of biological control, particularly in sensitive areas such as importation and genetic manipulation. Only in this way will they generate the confidence of public and government alike, and thereby the freedom to pursue their discipline to its full potential.

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Registration and regulation in biological control

J. Byrne
Pesticides Directorate, Agriculture Canada, Ottawa, Ontario K1A 0C6

ABSTRACT *Agricultural products are regulated in Canada under the Seeds Act, the Animal Health Act, the Feeds Act, the Plant Protection Act, (replaced by the Plant Quarantine Act as of October 1, 1990), and the Pest Control Products Act. Regulation of biocontrol products falls under the jurisdiction of the Plant Protection Act and the Pest Control Products Act. Plant Protection regulates plant pests imported into Canada or movement of plant pests within Canada. Pest risks are evaluated by Plant Protection and Research Branch scientists, and the United States Department of Agriculture is usually consulted. The Pest Control Products Act requires that all pest control products be registered prior to their manufacture, sale or use in Canada to ensure the safety, merit and value of products used. Guidelines or "Memoranda to Registrants" outlining data requirements for research permits and registration of microbial pest control agents are currently available. These guidelines will serve as the basis for developing data requirements for genetically modified microorganisms.*

INTRODUCTION

Agriculture Canada is divided into three main Directorates under which different agricultural products are regulated. A description of some of the activities associated with each of the regulatory groups follows:

Seeds Act The Seeds Division, under this Act, regulates inspection, testing, quality and sale of seeds and plant propagules of all types. Imported seed must be safe, efficacious, viable and pure under this Act.

Animal Health Act The Animal Health Division, under this Act, regulates the production, evaluation, importation, distribution and disposal of veterinary biologics, animal products and byproducts, and animal pathogens. This includes live or killed microorganisms, diagnostic reagents produced by traditional or new biotechnological processes, and indigenous or imported animal pathogens and materials of animal origin.

Feeds Act The Feeds Division, under this Act, handles feeds and feed additives, including probiotics. They handle pre-sale registration and post-sale inspection for the manufacture, sale and importation of livestock feeds and feed ingredients.

Fertilizer Act The Fertilizer Division, under this Act, regulates the sale and distribution of fertilizers and supplements. This includes naturally occurring and genetically modified organisms.

Plant Protection Act and **Pest Control Products Act** These Acts cover most aspects of biological control. The Plant Protection Act (effective October 1, 1990) regulates all imported products and includes biocontrol agents such as nematodes and insects. This Act is used to prevent the introduction of potential plant pests into Canada or movement of pests between provinces. Pest control products are regulated in Canada under the authority of the Pest Control Products (PCP) Act and Regulations, administered by the Pesticides Directorate. The PCP Act requires that all chemicals and microbial pest control products be registered prior to their manufacture, sale or use in Canada. Under this Act, a pest is defined as: "any injurious, noxious or troublesome insect, fungus, bacterial organism, virus, weed, rodent, or other plant or animal pest, and includes any injurious, noxious or troublesome organic function of a plant or animal." A control product is defined as: "any product, device, organism, substance, or thing that is manufactured, sold or used as a means of directly controlling, preventing, destroying, mitigating, attracting or repelling any pest." Thus, the PCP Act regulates a range of products including chemical products (herbicides, insecticides, etc.), biochemicals (including growth regulators and pheromones), and microbial pest control agents (including bacteria, fungi, algae, protozoa, viruses, mycoplasmae or rickettsiae, and related organisms that have a pesticidal claim).

The purpose of regulation is to ensure the "safety, merit and value" of products used. Towards this end, it is the role of the regulator to address the safety of consumer products, ensure protection of the environment and ensure efficacy and value of products. Data submitted by companies and researchers must address scientific issues including product identification; human health concerns; environmental concerns; possible effects of both small and large-scale field testing; and merit and value, before commercialization. Agriculture Canada regulates all aspects of product development from testing in the field to the registration of a product for sale.

When these data are submitted, the Pesticides Directorate of Agriculture Canada requests reviews from its advisors in other federal departments. Health and Welfare reviews human health safety and food residue data, Environment Canada assesses risks to the environment and non-target organisms, Fisheries and Oceans assesses aquatic data and Forestry Canada may be involved in aspects related to forestry applications. Evaluation is therefore a team approach and risks and benefits are considered to reach a best-balanced decision. Agriculture Canada conducts the risk benefit analysis (where necessary) and makes the final regulatory decision after considering the reviews from the advisors.

Guideline development also benefits from this team approach. In addition, consultation with other groups including industry, researchers and users is achieved in a variety of ways, e.g. workshops, such as the two workshops on Naturally Occurring and Genetically Modified Pest Control Agents, held in 1989 and 1990 respectively; Memoranda to Registrants (R-Memos) and Trade Memoranda (T-Memos); Backgrounders; and Working Papers. R-Memos are used for documents in draft stage and are issued for public comment (usually a 3-month period). T-Memos are used to issue final guidelines after consultation is complete.

BIOLOGICAL CONTROL

Many biological protection strategies are being used as alternatives to the use of synthetic chemical pesticides and are classified as "classical" or "inundative" control. The classical biocontrol refers to imported, exotic control agents (which can also be used inundatively e.g. nematodes) and the use of microbial pest control agents is an inundative control. Microbial pest control agents can be applied in a manner similar to chemicals (i.e. each season or several times in a season) or they can cause an epizootic. If they are able to perpetuate themselves, no further applications or infrequent applications will be required.

Biological control has resulted in some significant successes in controlling certain insect pests and weeds. There is also potential for much greater use of naturally occurring microorganisms for pest control. This area will be impacted by biotechnology where genetic modification can enhance desirable characteristics.

Biocontrol products such as insects to control weeds are assessed by Research Branch in conjunction with Plant Health and usually in consultation with the US Department of Agriculture. Insects are handled by the entomologists in the diagnostics services section of the Research Branch. Nematodes are often reviewed by Animal Health Group and sometimes Research Branch is contacted to help in the reviews.

In Canada, most of the microbial pest control products currently registered are for products containing *Bacillus thuringiensis* Berliner (*B.t.*) as the active ingredient. Microbials are defined as: "Organisms which are bacteria, algae, fungi, protozoa, viruses, mycoplasmae or rickettsiae or related organisms."

In a comparison between microbial products from the USA and Canada, the USA is not far ahead in terms of the numbers of active ingredients registered. The numbers of research permits have risen at a fast rate over the last ten years and the activity in this field of research is ever increasing as an alternative to the use of chemicals. The interest in the use of microbial pest control agents results from their high specificity for the target organism. Their use is therefore more attractive from an environmental safety standpoint but less attractive from a commercial standpoint.

MICROBIAL PEST CONTROL AGENTS

The first microbial pest control agent, *Bacillus thuringiensis* Berliner (*B.t.*), was registered in 1962 for control of lepidopterous pests on agricultural crops. At that time, no guidelines were in place and products were assessed on a case-by-case basis. At this time, most of the focus was on the performance of the product. Things have changed significantly since 1962. We now have a total of 50 microbial registrations which include primarily subspecies of *B.t.* and baculoviruses.

As a result of the workshops mentioned earlier, R-Memos, or draft guidelines are now available for both the field testing and registration of naturally occurring organisms (NOMs). NOMs have been defined as: "organisms isolated from nature or selected by strain improvement or developed by natural mechanisms e.g. transformation, conjugation within some species."

These memoranda do not cover importation of these products, nor do they deal with requirements for genetically modified microorganisms (GMMs). The intention of these guidelines is to provide a framework for both the registrant, researcher and the regulator. Because of the uniqueness of microorganisms (e.g. limited host range, ability to multiply, disseminate, and generally lower application rates), the specific requirements are likely to change as our knowledge base expands. These guidelines have attempted to outline appropriate science-based requirements to evaluate the safety, merit and value of the products. However, submissions will be evaluated on a case-by-case basis due to their unique nature. Waivers for certain data may be granted. Applications for waivers must be supported and accompanied by a sound scientific rationale.

As mentioned earlier, these guidelines are partly the result of a workshop held in March 1989 and the recommendations resulting from this workshop. The initial guidelines were drafted in 1986. However, due to time constraints, these guidelines may not reflect, in full, the recommendations that came out of our workshop. These areas where agreement needs to be reached will be dealt with later.

R-Memos and T-Memos have a 3-month comment period. The comment period for Research Permit Guidelines was from June to August and the comment period for Registration guidelines is from August to November. The Research Permit comment period will be extended to coincide with the Registration guidelines comment period.

REGISTRATION GUIDELINES

The following discussion will deal with basic data requirements for registration of a naturally occurring microorganism (NOM) to give an overview of a "typical data package". The registration package is divided into 8 different components, the first of which is an index listing of all the studies, methods, papers, etc. submitted. The section numbers reflect those found in the chemical guidelines for internal administrative reasons. Part 1 deals with information required for the product label such as use rates, application methods, and precautionary statements/hazard warnings in English and/or French.

Part 2, or product chemistry requires information on taxonomy and detailed characterization of the strain including genetic/molecular, biochemical and microbiological data. Source of the strain, its history, maintenance, and genotypic/phenotypic stability are also necessary. In addition, a description of the manufacturing methods including quality control procedures to ensure the integrity of the active ingredient and freedom from harmful contaminants or extraneous matter must be given. Data relating to the storage stability and description of conditions for storage of the end use product are requested.

Human Health and Safety are covered in Part 3. Minimal safety requirements included are acute oral, dermal and inhalation infectivity/toxicity studies for both the active ingredient and formulated product. A 30 day feeding study on the active ingredient is required for products to be used on food or feed. These above mentioned studies involve single high doses and are required to assess the capability of all microbial pest control agents to cause disease. Other possible additional data requirements for initial safety testing for both food and nonfood uses may include teratology, reproductive, oncogenicity and pharmacokinetics. The inclusion of these requirements is currently under consideration.

A single high dose of the active ingredient is applied in one of three ways depending on the organism. Intravenous injection is used to test bacterial and viral infectivity, intraperitoneal injection is used to assess fungal and protozoan infectivity and intracebral injection is used for neurotropic agents.

Irritation studies, and hypersensitivity studies are required to assess the potential of the microorganisms themselves or component(s) in the formulated product to cause skin or eye irritation or hypersensitivity, respectively.

Tissue culture studies are only required for viral agents and determine carcinogenicity and/or infectivity in mammalian cells.

Testing of genotoxic potential is required because of the possibility of microbial organisms producing toxins and /or metabolic byproducts which may cause genotoxic effects. These studies are designed to detect gene mutations and chromosomal aberrations.

Assessment of exposure requires that the potential for occupational and bystander exposure be fully detailed. This includes information on the use pattern, application equipment and methods, application rates, frequency of application, crops treated, persons potentially exposed, and decontamination procedures.

Part 5, dealing with food and feed residues, requires data to assess the exposure of humans and livestock to potential residues in food and feed. Use of a microbial control product on food requires the establishment of residue limits or an exemption under the Food and Drugs Act and Regulations. If a microbial agent is suspected, in safety testing, to produce a toxin or if residues of a toxic metabolite are present on food crops at harvest, then the microbial pest control agent may be subject to the same residue requirements that chemical pest control products currently undergo. A microbial agent may be considered for exemption on a case-by-case basis if supported by appropriate and sound scientific rationale.

Environmental Fate in Part 6 as a requirement, is determined by the results of the toxicology testing as outlined in Part 7. Environmental fate is necessary for microbial agents that demonstrate poor host specificity or show significant effects on nontarget organisms.

At this point, two concepts adopted by Environment Canada should be discussed. The first of these involves the definition of indigenous and nonindigenous microorganisms. Indigenous refers to microorganisms that occur naturally in the ecozone of intended use of the final product and nonindigenous refers to microorganisms that occur naturally in an ecozone different from the ecozone of intended use of the final product. The second concept is the ecozone referred to in the above definitions. Ecozones are defined as: "large and very generalized ecologically distinctive areas based on the interplay of landform, water, soil, climate, flora, fauna, and human factors. The boundaries between ecozones should be viewed as transitional areas, rather than discrete lines of demarcation."

Environmental toxicology testing in Part 7 is required to assess possible affects of the microbial pest control agent on nontarget organisms in terms of infectivity, pathogenicity/toxicity, and hypersensitivity. Testing is done on a Tier system approach where Tier I outlines the minimum requirements for the formulated product. Nontarget organisms are exposed to a maximum challenge concentration (1000× maximum expected concentration in environment) in Tier I. Tier II, III, and IV testing is done for all nontarget organisms showing visible effects at increasingly affected degrees.

Nontarget organisms are selected on the basis of the proposed use pattern of the microbial agent. Criteria to select nontargets include host range or the degree of specificity of the control agent (determined by testing of taxonomically similar organisms); organisms known to be infected by the microbial agent; nontargets susceptible to pathogens closely related taxonomically to the microbial agent that are economically or ecologically important; nontarget organisms having the greatest exposure to the agent; and, those that are morphologically, physiologically or biochemically similar to the target organism.

Representative nontarget organisms are selected from the following groups of organisms: birds, mammals, fish, invertebrates (aquatic and terrestrial), microorganisms, and plants. Exemptions may be applied for the testing of some groups of nontarget organisms depending on the biology and ecology of the microbial agent. Appropriate scientific rationale based on documented studies must accompany these applications.

Types of testing should mimic the natural mode by which the organisms would be exposed in the environment as much as is possible. For example, birds would normally be exposed via their diet or respiratory tract. However, in this case, respiratory studies are impossible to do. Fish would be exposed through their food or directly from the water itself.

The last section in the registration guidelines deals with the generation of efficacy data. This data is derived from both laboratory and field trials and is required for all formulated products. Data may be used from other countries to supplement Canadian trials.

RESEARCH PERMITS

All potential products must be field tested to determine if they merit registration. These include new uses for registered products, new formulations and new sources of registered products, and new active ingredients. However, before field tests can be done, risks associated with field trials must be evaluated. For this assessment, a basic information package about the organism and proposed test is required. The guidelines have an exemption from the requirement for a research permit (to allow some flexibility) for field testing of indigenous organisms. This exemption only applies for trials on less than 10 hectares, on property owned or operated by research institutions with no cooperators, using proper precautions and safety equipment and on a crop destruct basis.

KEY ISSUES

Some of the key issues that came out of the recommendations from the 1989 workshop include the following areas: definition of active ingredient, endpoints for safety testing, "Ecozone" concept, identity/taxonomy of microorganisms, and residue requirements. The most recent workshop on GMMs readdressed these concerns and further recommended that the definition of GMMs be re-examined and a data base be established.

Definition of Active Ingredient The definition of active ingredient currently in the guidelines is: "Microbial entity (and any associated metabolites) to which the effects of pest control are attributed inclusive of any growth media required to maintain viability or activity of the microorganism". Recommendations have been to add the word "living". However, addition of this word would reduce the flexibility to evaluate all types of microbial products.

Endpoints for Safety Testing Unlike the US safety testing requirements, Canada still has hypersensitivity testing. In addition, the 30-day feeding test is a test requirement unique for Canada. Clarification of the waiver clause for this test has been recommended. Other recommendations focused on changing or eliminating endpoints such as: eliminate daily body temperature readings, blood chemistry and serology, to require histopathy only in cases where lesions occur and in cases where the organism persists in the body of the test animal. These issues remain unresolved.

Ecozone Concept This concept was originally proposed as a way to assess whether an organism was indigenous or not. This classification affects the extent of data required and also whether a product fits under the exemption given for field trials. Practically, it is difficult to define how "similar" is similar. In addition, how does one prove an organism occurs naturally in an ecozone? It has been suggested by some that indigenous be considered continental and nonindigenous as off-continent with the provision that organisms from very different "ecoregions" or "ecozones" may require some additional data. It was recommended in the 1989 workshop that the "ecozone" concept not be implemented as proposed by Environment Canada.

Identity/taxonomy The question of the level of detail and information on description is the concern. Taxonomic identification must be thorough but the level of detail will vary according to the organism. Strains should be unequivocally differentiated.

Residue requirements At present, these requirements may be requested in cases where the product is to be used on a food crop. Exemptions may be considered. In contrast, the US guidelines do not always require residue data.

Contamination and quality control Various recommendations were made such as that human health risk contaminants should be absent in the product. In addition, good manufacturing practices should be used in plants and for monitoring. Finally, contaminants should be specified in the product specifications and Quality Assurance Program sections; and the types of contaminants must be known before standards can be set.

GMMs Agriculture Canada plans to build on the two guidelines for NOMs. The concept of regulating the product, not the process, has been agreed upon, since GMMs are not considered to be a unique category requiring special treatment. However, the definition of GMMs needs to be revised to include all products that will require regulation under this category. In addition, agreement as to which products should fall under this category needs to be reached. For example, products of genetic engineering include deletions and additions. Do these products need to be regulated equally? How should killed products which are genetically modified be handled?

CONCLUSION

This paper has attempted to give a brief overview of regulations applied to biological control within Agriculture Canada. Different agricultural products are regulated under one of six acts. Biological pest control products are regulated by the Pest Control Products Act. Researchers must therefore report to the government when a product or active ingredient will be imported, before products are field tested, and for registration of a product before commercialization. Imported biocontrol agents such as nematodes, insects, etc., fall under the Plant Protection Act and are evaluated by the Research Branch and Plant Protection Division of Agriculture Canada in consultation with the United States Department of Agriculture. With the advent of commercialization of some of these products, issues such as efficacy and quality control may need to be addressed.

The assessment of microbial pest control agents is done by a team approach. Components of the data packages are sent out to the appropriate federal advisors for evaluation and assessment

Guidelines for the regulation of naturally occurring organisms are now available as an R-Memo with a comment period ending at the end of November. Consultation is an important component in the development and refinement of these guidelines. I encourage you to input on these guidelines in writing. If any of you have not received a copy of these guidelines and would like to, please do not hesitate to contact the Pesticides Directorate at (613) 993-4544.

Building Biological Control Institutions for the Twenty-first Century

R.G. Van Driesche
Department of Entomology, University of Massachusetts, Amherst, Massachusetts 01003, USA

ABSTRACT *Institutions for the conduct of biological control need rebuilding if the method is to address a significant share of pest problems in North America. A comprehensive approach to the implementation of biological control is now used in Massachusetts. It includes (1) planning — to correctly identify pests against which biological control is most likely to succeed; (2) leadership — vesting overall program direction in a Biological Control Coordinator; (3) funding — creation of state sources of competitive funding for applied biological control research and implementation; (4) communication — newsletters, training days and other tools; (5) agricultural extension — to help extension agents develop the skills to understand and promote biological control and (6) biological control teams — formal groups of researchers and extension agents which plan and conduct biological control projects. These steps can be used to develop an integrated, comprehensive program for biological control. Such an approach is essential if the method is to be utilized widely enough to be a major form of pest control for the future.*

INTRODUCTION

While the scientific basis to conduct biological control in North America is stronger now than it was 30 years ago, the institutional capacity for the task is not. Laboratories have been closed or reoriented to different tasks, biological control scientists transferred or nudged into retirement, positions lost, institutions eroded. Now, as the public shows ever more desire for ways other than pesticides to control pests, our capacity to conduct applied biological control has diminished. While as biological control scientists, we find our pleasure in the biology that is the heart of biological control, it is to the drier, less exciting task of rebuilding biological control institutions and the public policies that guide them, that we must now turn if biological control is to regain its capacity to identify and solve its share of society's pest problems.

In my talk today I will focus on efforts in Massachusetts to rebuild a capacity for biological control. I will identify and comment on the components that are in my opinion essential for a strong institutional capacity for biological control activities. These components, (1) planning, (2) leadership, (3) funding, (4) communication, (5) agriculture extension, and (6) teamwork, form the basis of the Massachusetts Biological Control Initiative (Van Driesche 1990), but are equally important in the process of rebuilding a strong institutional capacity for biological control at the national level in the USA and, I suspect, in many other countries as well. For each component I will illustrate the difference between where we need to go and where we are likely to be if we make no concerted effort to rebuild our biological control institutions.

COMPONENTS OF THE MASSACHUSETTS BIOLOGICAL CONTROL INITIATIVE

Planning Which pests we choose to mount biological control projects against is a major determinant of the success that results and the value these efforts have to society. That projects should be selected wisely is therefore critical. Efforts however to systematically assess the potential for the application of biological control to the pest problems in a state, province or country are rare. Among the few examples are those of Alberta (McClay 1989) for weeds and

Massachusetts for crop insects and mites (Van Driesche and Carey 1987). Planning seeks to guide decision making so that selection of biological control targets is based on both (1) the importance of the problem economically and (2) the odds, in view of the pest's biology and what we know of its natural enemies and those of related species, of successfully achieving biological control of the pest. Information on the extent of losses from the pest must be gathered from surveys, either of growers or of persons, such as commodity entomologists, who are aware of the commonness, frequency and severity of losses from individual pest species in the crop. Estimates of the potential for biological control of a given species come from information in the scientific literature on the natural enemies of the pest and its relatives and from the judgment of biological control specialists in view of the characteristics of the pest's life history, ecology, and taxonomic placement. McClay (1989), for example, develops a point system for assessing the probability that a weed species could be effectively and acceptably controlled by biological control methods.

Planning allows opportunities for biological control projects with high probability of success against less critical pests to be recognized as profitable opportunities to reduce, in moderate steps, the pest burden on crops. It also shows the inadvisability of mounting projects only against a small number of economically critical pests if these, as is often the case, have only a low probability of being successfully controlled through the use of biological control. Despite these advantages, planning is rare. Target pests are most commonly selected for political reasons or, owing to the newness of an invasion, are cases in which the pest is clearly seen by the public to be an invader — e.g. ash whitefly in southern California (Sorensen et al. 1990).

While it is unlikely that political considerations will ever be totally eliminated from the process of funding public pest suppression activities, states would be well served by adopting systems utilizing more objective selection criteria, based on planning and review of the scientific literature. This should begin with the production of a planning document on the region's pests of the type exemplified by McClay (1989) and Van Driesche and Carey (1987). Federal priorities could then be identified through compilation of state- or province-level priorities.

Leadership For biological control to be well utilized we need leaders and lead institutions that, within a state, province, or nation, will speak for biological control, articulate sound policy, encourage completion of needed research, nudge, educate and link persons together in efforts to achieve biological control.

At the state or province level, biological control activities are present (1) at Universities, (2) in laboratories supported by state departments of agriculture, and (3) in private institutions. University activities are likely to be concentrated in departments of entomology and to consist of programs developed by commodity entomologists who, as part of their efforts to meet the pest management needs of their growers, have invested effort in the study and implementation of biological control methods for one or more pests attacking the commodity. If no entomologist has been assigned responsibility for a given commodity, or if the responsible entomologist is not interested in biological control, opportunities to apply biological control in the crop, no matter how promising, will be missed.

State biological control laboratories (as in New Jersey, Hawaii, Oregon, North Carolina) often work independently from and unconnected to University programs within the same state. Projects on which these laboratories focus are determined by administrative decisions and agendas are likely to be responsive to expressions of grower concern.

Private institutions (e.g. commercial insectaries, etc.), are likely to either be commercial ventures or public interest institutions. Commercial insectaries are of necessity motivated by profits and hence must work primarily on large-market pests, seeking solutions that can be packaged, sold, and used effectively when and where applied. Such institutions are unlikely to address many important pests for which the public needs relief, but which are unprofitable.

How then can leadership arise given this range of players? In Massachusetts we have used the existence of the position of "Biological Control Coordinator" as a means to develop such leadership. This position, based in the Department of Entomology at the state land grant university, is jointly funded and supervised by the Massachusetts Department of Food and Agriculture and the University of Massachusetts. It is physically based at the University and integrated into the Department of Entomology. Most importantly, the position is not responsible for any particular commodity, but rather specifically charged to give leadership, both in terms of research, extension and state policy development, to biological control as a whole, seeking out good opportunities for biological control in whatever commodities they occur. Programs are developed both independently and cooperatively with commodity entomologists based on mutual interests. The concept of a Biological Control Coordinator and duties of such a position have been discussed by Van Driesche (1989). The Biological Control Coordinator can provide leadership in a number of key areas: (1) He/she can initiate and see to the completion of a state wide planning process to identify biological control opportunities within the state's various commodities. (2) He/she can initiate research on projects identified in this planning process, either alone or cooperatively with others. (3) He/she can serve as a source of information for interested persons in the state on biological control and the status of current projects around the state, region, nation or world. (4) He/she can stimulate and encourage others to engage in biological control research and implementation. (5) He/she can make needed importations of new biological control agents. (6) He/she can train extension agents in biological control concepts and details, and can write fact sheets on the biological control of individual pests or pest groups. (7) He/she can work with state government to develop sources of funding for biological control activities, both research and extension. (8) He/she can provide leadership in developing state policies regarding biological control. (9) He/she can represent the state's interests and reflect its accomplishments to national and international groups and bring back to his state new ideas or biological control agents in use elsewhere.

In the absence of a Biological Control Coordinator, biological control projects can occur, but a comprehensive program is unlikely to develop. Creation of such a position, with a strong mandate and well positioned in the state or province's institutions, is the single most powerful mechanism to provide leadership to develop a well organized program of biological control. In general, few states or provinces have taken this step. Texas and Massachusetts have to a degree. Most other states have not and could benefit from creation of such positions.

Leadership institutions are also essential at the national level to establish policy, develop laboratory and field facilities, and carry out programs. The USA currently lacks an effective leadership structure for biological control. ARS (Agriculture Research Service), the agency responsible for USDA-sponsored biological control research, is administratively divided geographically and has weak national-level integration of its Biological Control Program. Regional laboratories with biological control scientists are administered by persons from other disciplines. Recently, another branch of USDA, APHIS (Animal and Plant Health Inspection Service) has developed interest in and capacity for biological control, including foreign collection of new agents. This is an outgrowth of its history of service in the redistribution of proven natural enemies (as in the alfalfa weevil and cereal leaf beetle programs).

Currently a "Biological Control Institute" is being developed by APHIS as an information centre on biological control. Efforts to coordinate APHIS and ARS policies and actions are under discussion, but not yet a fact. Development of a national policy on biological control is further complicated by the need to create a mechanism to harmonize not only the programs of APHIS with those of ARS, but also to take into account programs in 50 states. The brightest federal-level development in biological control institutions has been the creation of biological control bilateral laboratories in China and the USSR, effectively opening these regions to exploration by US biological control scientists.

Funding In the course of creating a biological control capacity within a state or nation, funding for applied research is critical. The value of thoughtful planning and decisive leadership will be reduced severely if motivated researchers are unable to secure funds to carry their ideas into action. In the USA, funding for applied biological control is scarce. At the federal level, competitive funds (through the USDA, principally) are directed at theoretical issues and ideas, not at conducting applied biological control programs. A researcher would, for example, be more likely to secure funds to study the theoretical implications of parasitoid egg load limitation or sex ratio allocation than to introduce, establish and evaluate a set of new biological control agents against some particular pest, say the filbert aphid or the sweet potato whitefly. Efforts to correct this problem have begun that seek to establish a separate competitive grants program for applied work. It does not exist, but is badly needed.

The alternative method of funding applied biological control at the federal level is through direct congressional appropriation. Funds arise through the efforts of congressmen concerned about a particular pest affecting their constituents. These moneys are inserted in agency budgets (USDA, NIH, etc.) and are earmarked for work on a particular pest (recent examples include pear thrips and deer tick). Agencies in whose budgets the funds are placed then either use the funds to develop their own program, or pass them on to state-level institutions (often researchers in land grant universities) through cooperative agreements. Much work on gypsy moth parasites and population dynamics, for example, has been funded in this way. This method is inferior to an open competitive process for two reasons. First the selection of which pests to work on may be less than ideal. The choice is likely to be based heavily on the seriousness of the losses caused by the pest, with little or no assessment of the probability of successfully using biological control against the pest. A second problem is that there is no peer review governing the selection of which researchers and which proposals actually get funded, decisions being made administratively by the agency developing the cooperative agreement.

Any political unit wishing to promote applied biological control would be well served by creating a stable, ongoing fund of money to be disbursed on a competitive peer review basis with all researchers welcome to submit proposals regardless of their institutional affiliation. Program guidelines should be developed giving a clear definition of what constitutes biological control and emphasizing that each proposal should have applied objectives related to reducing, through biological control means, a significant pest problem.

State or province-level funds can also be a vital source of funding for biological control activities. Creating a state-based system requires first that an atmosphere of legislative support for biological control be developed so that funds are made available in regular annual appropriations. Second, through the leadership of the Biological Control Coordinator, a plan must be devised to award funds to those researchers with the best ideas as measured against state priorities. (These priorities are ones those previously established through a systematic planning process). In Massachusetts $80,000–$100,000 of such money has been available in each of the last four years (fiscal years 1987–1990). These funds are awarded competitively based on proposals submitted by interested researchers, both public and private. In the past fiscal year, for example, these funds supported work on (1) effects of reduced spray programs in apples on parasites of apple leaf miners, (2) possibilities of using corn/potato rotations to enhance predators of Colorado potato beetles, (3) a study of the feasibility of the use of a parasite of the deer tick to lower tick populations in parts of Massachusetts, and (4) studies of antagonistic fungi to control strawberry diseases. Existence of state funds has very positive effects because these funds can be used to entice interested but hesitant researchers into biological control. Also they give the state "purchasing power" to direct research activities towards specific problems and make possible applied studies that currently are very difficult to fund in the USA at the federal level.

In addition to national and state-level public funds, other funds from private sources such as grower groups may exist in some areas.

The challenge for biological control is to expand the amount of funding available and to use it wisely by directing it, competitively, to the best researchers, and against well chosen target pest species.

Communication The existence of a Biological Control Coordinator facilitates the organized communication of information about biological control projects and related developments. Communication links are needed that inform extension agents and state officials within the state of project results. Simultaneously, links to other biological control scientists in the region are needed. In Massachusetts these needs are being met through two newsletters. One, entitled Biocontrol Flash, reaches extension agents primarily, but also key officials who make administrative decisions affecting funding for biological control activities. This newsletter is limited to a small number of persons (about 100) so that it can be mailed by first class postage for speedy delivery. Articles cover developments in state biological control projects or other news, national or international, from which extension agents would benefit. A second newsletter, entitled "Natural Enemy News", reaches about 150 biological control scientists in 13 US states and 5 Canadian provinces. This newsletter allows researchers to share ideas about projects and interests, stimulating cooperation among researchers in separate institutions or separate states or provinces.

Another vehicle for communication is attendance at meetings. In the northeast, we have recently (1988) formed a working group on biological control, similar to those that have been in existence for many years in other regions, but were lacking in ours. An annual meeting allows people to meet and discuss project results and issues of common interest such as policy or funding. Within the state, an annual "in-service training day" for extension agents on biological control has been initiated that provides extension agents an opportunity to hear results of biological control activities across all commodities and to improve their understanding of biological control by discussion with the Biological Control Coordinator.

A third, and critical, avenue for communication is to provide information on biological control projects to state or provincial legislators who have provided the funds. In Massachusetts, such an activity was conducted for the first time in 1990, with researchers presenting results of their work in a day-long program held in the state capital building, thus making it easy for legislators to attend.

Agricultural extension Biological control programs, even the introduction of new beneficial species, need support from farmers if the target species is a crop pest. Farmers must understand and value biological control for the added security it brings them against rapid pest increases, and for the reduced need of pesticides it produces. To help farmers develop a better understanding of these ideas, and to provide them with the detailed information they need to integrate biological control into their farming practices, extension agents must be knowledgeable of both biological control concepts and the details of the biological controls for specific pests. The Biological Control Coordinator, again, is important in ensuring that agents understand biological control concepts and have the details they need on specific biological control agents for individual pests. One part of this need can be met through in-service training days on biological control for extension agents. In addition, written materials that cover biological concepts and details for particular pests will be needed. In general, traditional extension pamphlets provide little information on biological control of most pests. In Massachusetts, we have initiated a new fact sheet series called "Using Biological Control in Massachusetts" to correct this problem by providing more detailed, lengthier discussions of biological control agents and practices for particular pests, as well as photographs of key natural enemies. To date, sheets have been produced on the biological control of (1) Colorado potato beetle, (2) cole crop lepidopteran pests, (3) apple leaf miners, and (4) apple mites. Currently a longer bulletin on opportunities for biological control of pests of woody ornamentals is being developed.

Biological Control Teams The final component of the Massachusetts Biological Control Initiative has been the formation of teams of research and extension workers interested in particular pest problems. Massachusetts is a small state, surrounded by many other small states. Entomological institutions tend to be small, with researchers scattered. Working together offers a way to be more efficient by sharing resources and information. For example, parasites in culture in one state can be used to make releases in adjacent states. Parasites (or other natural enemies) available in one location but not in another can be exchanged. For example, Massachusetts has provided Ontario with a recently imported Chinese strain of *Apanteles rubecula* Marshall to use against imported cabbageworm, *Pieris rapae* L., and Ontario has provided Massachusetts with *Holcothorax testaceipes* (Ratzeburg) (originally from Japan, but previously introduced to Ontario) for release against apple blotch leaf miner, *Phyllonorycter crataegella* (Clemens). Teams are currently in existence for three projects: imported cabbageworm, using *Apanteles rubecula*, a parasitoid, with participation by Ontario, Massachusetts, Rhode Island, and Connecticut; euonymus scale, using *Chilocorus kuwanae* Silvestri, a coccinellid, with participation by extension agents in various parts of Massachusetts; and birch leaf miner, *Fenusa pusilla* (Lepeletier), using *Lathrolestes nigricollis* (Thomson), with participation by New York, Massachusetts, Connecticut, Rhode Island and Ontario. Teams also allow researchers to develop personal acquaintances that in turn promote further cooperation.

CONCLUSION

The Massachusetts Biological Control Initiative represents a state-level attempt to systematically redevelop an infrastructure to support the conduct of biological control. The role of a Biological Control Coordinator is central to this process as it provides leadership in the development of many of the other components. Ad hoc unplanned biological control activities in a state or province sometimes flourish, but do so erratically and rarely lead to development of well conceived institutions capable of sustained biological control activities. To maximize the degree to which biological control is put to work solving pest problems for society, a more deliberate, organized approach is needed. It is to this end that senior biological control scientists should address themselves. Steps are urgently needed now to check the decline of biological control institutions. These institutions need increased funding, new positions, clear goals and strong leadership. Achieving this will open the way for application of biological control on a vastly wider scale in the next several decades than we have experienced in the recent past.

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SESSION 4: THE WAY AHEAD

On the afternoon of October 12, participants at the workshop divided into four smaller groups to discuss four areas affecting the future progress of biological control in Canada. After the discussion group sessions, the moderator of each group presented a report to the full meeting on the recommendations or concerns which had been raised in the group. The following summaries are based on videotape transcripts of the moderators' reports.

GROUP A: RESEARCH NEEDS

Moderator: W. Turnock, Agriculture Canada

The following areas were identified by this group as being critical for further research, or as affecting Canada's research capacity in biological control:

1. **Pest ecology and population dynamics** Many projects fail for lack of information on the population dynamics and ecology of the target pests. The existing natural enemy complexes of many pests are poorly studied, and this hampers evaluation of the effects of introduced biocontrol agents.

2. **Taxonomy** The ability to identify accurately pests, natural enemies and host plants occurring in Canada is crucial to biological control. Concerns were raised about the continuation of support for taxonomic research in Canada, in particular the Biosystematics Research Centre of Agriculture Canada. The taxonomy of insect pathogens was identified as an area of particular weakness.

3. **Integration with agricultural practices** Little is known about the impact of agricultural practices on biodiversity and natural enemy communities, or about ways of modifying agricultural practices to enhance the impact of natural enemies. The possible use of semiochemicals to modify parasitoid behaviour should be studied.

4. **Biopesticide research** Further study is needed on the compatibility of biopesticides with other biological control agents and with chemicals, on the effects of environmental conditions on efficacy of biopesticides, and on the possible development of pest resistance to biopesticides.

5. **Classical biological control** There is a need for more intensive pre-introduction study of the biology of candidate biocontrol agents. Over the long term this should improve our ability to predict success in biological control and select the agents most likely to be effective.

6. **Information exchange** There is a need for a forum for exchange of information in biological control research.

GROUP B: COORDINATION AND FUNDING

Moderator: P. Harris, Agriculture Canada

The members of this group felt that much biological control work is being done in Canada in relative isolation, and that there was a need for a forum to bring together those interested in biological control and thus increase the effectiveness of their efforts. They therefore presented a single recommendation: that there should be formed a "Canadian Forum for Biological Control". The mandate of this organization would be to provide leadership in biological control, set priorities at a national level, and promote communication among all those interested in biological control. As a first step they proposed that a temporary executive should be nominated, consisting of a chairperson, a vice-president representing biological control of insect pests, and a vice president representing biological control of weeds. The temporary executive would have the job of forming a board with regional representation from across Canada, investigating the mechanics of forming the organization, and drawing up draft proposals for a constitution. These draft proposals would be published for comment in *Biocontrol News*, the annual newsletter on biological control produced by Agriculture Canada. All participants at the Workshop will receive a copy of *Biocontrol News*. On the basis of comments received, a revised version of the constitution would be drawn up and distributed. The next national biological control meeting would then be the inaugural meeting of the Forum. It was suggested that this be held in conjunction with another national meeting such as one of the Expert Committees, the Entomological Society of Canada or the Canadian Phytopathological Society. (The fact that this Workshop immediately followed the annual meeting of the Entomological Society of Canada in Banff has made it easier for many to attend.)

As noted in the Preface, this recommendation was unanimously endorsed by the Workshop participants. A temporary executive was elected and draft proposals for the Canadian Forum for Biological Control will appear in the next issue of *Biocontrol News*.

GROUP C: REGULATION

Moderator: R. Burland, Alberta Environment

This group attempted to consider the current status of regulation of biological control in Canada, and then went on to consider possible future changes. Two main areas were considered: biocontrol agents not presently regulated under the Pest Control Products Act, and those which are so regulated.

The first group covers agents such as arthropods, vertebrates and nematodes. At present these are regulated only as regards their importation into the country, with some provinces also requiring approval for movement across provincial borders. It was brought out in discussion that such agents could in principle require registration under the Pest Control Products Act, but that no regulations to enforce this are in place. There was a concern that attempts to bring such agents within the regulatory framework might lead to excessive or inappropriate regulation. To avoid this risk it was suggested that codes of practice should be drawn up by groups involved in the use of these agents. The Forum on Biological Control, proposed by the members of Discussion Group B, could be a suitable body to undertake this.

In the area of microbial agents, which are currently regulated under the Pest Control Products Act, the group identified three concerns:

1. There is a need for appropriate methodology for assessing chronic toxicity.
2. There is a need for methodology in environmental monitoring.
3. For agents whose toxicity is known to be negligible, the need for residue testing before registration was questioned.

GROUP D: IMPLEMENTATION

Moderator: W. Yarish, Alberta Agriculture

A number of points were identified by this group as being crucial to the successful implementation of biological control. These included:

1. **Training** Those involved in releasing or applying biocontrol agents must be trained in the proper methods of handling and utilizing them.

2. **Coordination** A biological control program may involve many people, including producers, landowners, extension staff, suppliers of biocontrol agents, and researchers. It is important for these groups to work together and be aware of each other's rôles, activities, objectives, and needs. It is also important that credit for successful projects should be shared among all those involved, for example by appropriate acknowledgments in research papers and reports. Failure to do this endangers future collaboration.

3. **Agent requirements** Information must be available on the climatic and habitat requirements of biocontrol agents so that they will not be released in unsuitable sites or areas.

4. **Propagation** A reliable source of biocontrol agents must be available, either through insectary rearing or field collection from established sites. Quality of agents used is crucial.

5. **Post-release monitoring** There was much discussion on monitoring the establishment and success of biocontrol agents, and whether this forms part of the implementation process or is a phase of the research project. The conclusion was that in biological control there is no sharp demarcation between research and implementation but rather there is a continuum: information from implementation needs to be continually fed back to researchers.

6. **Guidelines** Written guidelines or "recipes" need to be provided for users of biological control covering factors such as rates or numbers of agents to be used, timing of releases, and results to be expected. These guidelines must take into account the constraints of other production practices such as seeding and harvesting dates. They should give users a realistic understanding of the level of success to be expected, so that they can decide if this level of control is acceptable to themselves or their consumers. Guidelines should emphasize that biological control is a component of integrated pest management and should include information on how to incorporate biological control into IPM programs.

7. **Regulation** Biological control using insects, whether in classical or augmentative programs, is largely unregulated except at the stage of importation of exotic agents. There is a concern that this creates a potential for fraud, misrepresentation or false claims of effectiveness.

8. **Program delivery** Biological control services can be delivered either by the public or private sector. The private sector seems best equipped to provide services to intensive industries such as greenhouse production, and perhaps to annual cropping systems. On extensive, low-input areas such as rangelands, forests and public lands, public sector involvement in biological control programs seems essential. Adequate funding must be available for implementation of this type of biological control.

9. **Action plans** Coordinated action plans are needed to ensure that biological control is used to the best possible advantage and that opportunities for its use are not missed.

LIST OF PARTICIPANTS

The areas of interest indicated by each participant on his/her registration form are shown after the address. These may not in all cases indicate active current involvement in those fields.

Shaffeek Ali
Crop Protection Branch, Alberta Agriculture, 7000-113 Street, Edmonton, Alberta T6H 5T6
— General biocontrol

Shelley Barkley
PO Box 35, Bassano, Alberta T0J 0J0
— Horticulture

Kal Basu
Alberta Wheat Pool, 505-2nd Street SW, Calgary, Alberta
— Greenhouses

Don Blumenauer
Ministry of Agriculture and Fisheries, 162 Oriole Road, Kamloops, British Columbia V2C 4N7
— Weed control, rangelands

Guy Boivin
Agriculture Canada, Research Station, 430 boul. Govin, St. Jean-sur-Richelieu, Québec J3B 3E6
— Egg parasitoids

Bart Bolwyn
Alberta Environmental Centre, Bag 4000, Vegreville, Alberta T0B 4L0

Edward Brouyette
Calgary Parks and Recreation Dept., PO Box 2100, Calgary, Alberta T2P 2M5
— Urban pests and weeds

Stewart Bryden
City of Calgary Parks and Recreation Dept., PO Box 2100, Calgary, Alberta T2P 2M5
— Trees

Rob Burland
Alberta Environment, 2nd Floor, Provincial Building, 200-5th Ave. S, Lethbridge, Alberta T1J 4C7
— Pesticide management

Joanne Buth
Manitoba Agriculture, PO Box 667, Carman, Manitoba R0G 0J0
— Weeds

Judy Butt
Alberta Special Crops and Horticultural Research Centre, PO Bag 200, Brooks, Alberta T0J 0J0
— Greenhouse insects and diseases

Joyce Byrne
Agriculture Canada, 2323 Riverside Drive, Ottawa, Ontario K1A 0C6
— Regulation, registration

Gary Byrtus
Alberta Environment, Pesticide Management Branch, 5th Floor 9820-106 Street, Edmonton, Alberta T5K 2J6
— Livestock, forest, urban and domestic pests

Carole Calenso
Olds College, Olds, Alberta T0M 1P0
— Greenhouse and nursery crops

Héctor A. Cárcamo
University of Alberta, 101-10234 167 St., Edmonton, Alberta T5P 4H4
— Predation

June Carrington
Alberta Public Works, Supply and Services, c/o Reservoir Development, 4th Floor, College Plaza, 8215-112 St., Edmonton, Alberta T6G 5A9
— Rangeland, weed control, trees/shrubs

Norm Caukill
Alberta Agricultural Research Institute, PO Box 760, Caroline, Alberta T0M 0M0

David Clements
Queen's University, Department of Biology, Kingston, Ontario K7L 3N6
— Orchard pest management (mites)

Dan Cole
Crop Protection Branch, Alberta Agriculture, 7000-113 Street, Edmonton, Alberta T6H 5T6
— General biocontrol

Miles Constable
Environment Canada, Twin Atria #2, 4999-98 Ave., Edmonton, Alberta T6B 2X3
— Effects of pesticides on environment

Gary Cook
Calgary Parks and Recreation Dept., PO Box 2100, Calgary, Alberta T2P 2M5
— Urban pests and weeds

Doug Cooper
Field Crops Branch, Alberta Agriculture, Bag Service #47, Lacombe, Alberta T0C 1S0
— Crop production

Bob Copeman
University of British Columbia, Department of Plant Sciences, #248-2357 Main Mall, Vancouver, British Columbia V6T 2A2
— Plant diseases, mycoherbicides

Gary A. Craig
City of Saskatoon, Civic Buildings and Grounds, Pest Management, 1101 Ave P.N., Saskatoon, Saskatchewan S7L 7K6
— Urban pests, insects, weed control

Roy Cranston
Ministry of Agriculture and Fisheries, 17720-57th Avenue, Surrey, British Columbia V3S 4P9
— Weed biocontrol

James E. Cunningham
Philom Bios Inc., #104-110 Research Drive, Saskatoon, Saskatchewan S7N 3R3
— Microbial (particularly fungal) biocontrol agents

John Cunningham
Forestry Canada, Great Lakes Forestry Centre, PO Box 490, Sault Ste. Marie, Ontario P6A 5M7
— Viral insecticides

Troy P. Danyk
Simon Fraser University, Department of Biological Sciences, Burnaby, British Columbia V5A 1S6
— Agricultural entomology, biocontrol

Barb Deneka
University of Manitoba, Department of Entomology, Winnipeg, Manitoba R3T 2N2
— Biocontrol of pea aphids

Heather Dewar
University of Guelph, Department of Environmental Biology, Guelph, Ontario N1G 2W1
— Biocontrol of insects

Michael Dolinski
Crop Protection Branch, Alberta Agriculture, 7000 113 St., Edmonton, Alberta T6H 5T6
— Field crop pests

Lloyd Dosdall
Alberta Environmental Centre, PO Bag 4000, Vegreville, Alberta T0B 4L0
— Biocontrol of insect pests of field crops

Lorne Duczek
Agriculture Canada, Research Station, 107 Science Crescent, Saskatoon, Saskatchewan S7N 0X2
— Biocontrol of plant pathogens

Robert Dupree
Uniroyal Chemical, Elmira, Ontario
— Registration of microbials and genetically modified microbials

Marvin Dyck
Gustafson Inc., 462 Ave D. S., Saskatoon, Saskatchewan
— Biological fungicides

Linda Edwards
Integrated Crop Management Inc., PO Box 164, Okanagan Centre, British Columbia V0H 1P0
— Agricultural entomology

Roy Ellis
Prairie Pest Management, 207 Cullen Dr., Winnipeg, Manitoba R3R 1P5
— IPM

Martin Erlandson
Agriculture Canada, Research Station, 107 Science Cres., Saskatoon, Saskatchewan S7N 0X2
— Insect virology

Jessica Ernst
Calgary Parks and Recreation Dept., PO Box 2100, Calgary, Alberta T2P 2M5
— Biocontrol of urban pests and weeds

Rudy Esau
Alberta Special Crops and Horticultural Research Centre, PO Bag 200, Brooks, Alberta T0J 0J0
— Biocontrol of weeds

David Finnamore
Department of Agriculture, Plant Industry Branch, PO Box 60000, Fredrickton, Nova Scotia E3B 5H1
— Biocontrol of weeds and insects, extension entomology

Pam Fisher
Ministry of Agriculture, PO Box 587, Simcoe, Ontario N3Y 4N5
— Tree fruit IPM

François Fournier
Collège MacDonald, 4287 Boyer #1, Montréal, Québec H2J 3C0
— Lutte integrée

Brenda Frick
Crop Development Centre, University of Saskatchewan, Saskatoon, Saskatchewan S7N 0W0
— Weed management in annual crops

Randy Gadawski
The City of Winnipeg, 2799 Roblin Blvd., Winnipeg, Manitoba R3R 0B8
— Greenhouses, interiors

George H. Gerber
Agriculture Canada, Research Station, 195 Dafoe Road, Winnipeg, Manitoba R3T 2M9
— Insect pests of canola

Gary A.P. Gibson
Biosystematics Research Centre, Agriculture Canada, K.W. Neatby Building, Ottawa, Ontario K1A 0C6
— Parasitic hymenoptera

Linda Gilkeson
Applied Bionomics Ltd., PO Box 2637, Sidney, British Columbia V8L 4C1
— Biocontrol in greenhouses and interiors

Dean Greco
Parks Department, 3532-3 Ave. N.W., Calgary, Alberta T2M 0N7
— Pest control

Er-Ning Han
Département de Biologie, Université Laval, Ste Foy, Québec G1K 7P4
— Insect ecology, behaviour, genetics

Bruce Hancock
Integrated Pest Management, 5 Alderwood Rd., Winnipeg, Manitoba R2J 2K7
— Biological control (interior plantscapes)

Peter Harris
Agriculture Canada, Research Station, PO Box 440, Regina, Saskatchewan S4P 3A2
— Biocontrol of weeds

Dan Harvey
Saskatchewan Agriculture & Food, 133-3085 Albert Street, Regina, Saskatchewan S4S 0B1
—Vertebrate, field crop, insect, structural & livestock pest management

Colin Hergert
Calgary Parks and Recreation Dept., PO Box 2100, Calgary, Alberta T2P 2M5
— Biocontrol of urban pests and weeds

Jim Hole
Hole's Greenhouses and Gardens Ltd., R.R. #2, St. Albert, Alberta
— All biocontrol areas

Katrina Horne
City of Calgary, Box 2100 Stn. M, Calgary, Alberta
— Weed and pest control

Robert B. Hughes
Alberta Environmental Centre, PO Box 1209, Vegreville, Alberta T0B 4L0
— Weed biocontrol, insect rearing

Cheryl Huscroft
456 Northwest Blvd., Creston, British Columbia V0B 1G0
— Noxious weeds

Sheau-Fang Hwang
Alberta Environmental Centre, Bag 4000, Vegreville, Alberta T0B 4L0
— Biocontrol of plant diseases

Ron Jackson
County of Athabasca, Box 540, Athabasca, Alberta T0G 0B0
— Biocontrol of weeds and livestock pests

Robert Jaques
Agriculture Canada, Research Station, Harrow, Ontario N0R 1G0
— Microbial control, agricultural insects

Klaus Jensen
Agriculture Canada, Research Station, Kentville, Nova Scotia B4N 1J5
— Biocontrol of weeds

Dan Johnson
Agriculture Canada, Research Station, PO Box 3000, Lethbridge, Alberta T1J 4B1
— Biocontrol of grasshoppers

Jim Wm. Jones
Alberta Special Crops and Horticultural Research Centre, PO Bag 200, Brooks, Alberta T0J 0J0
— Parasitoids of field crop pests

Andrew Keddie
University of Alberta, Department of Entomology, #2-27 Earth Science Bldg., Edmonton, Alberta T6G 2E3
— Insect pathology (virology)

Scott Kellock
Calgary Parks and Recreation Dept., PO Box 2100, Calgary, Alberta T2P 2M5
— Biocontrol of urban pests and weeds

Prem Kharbanda
Alberta Environmental Centre, PO Bag 4000, Vegreville, Alberta T0B 4L0
— Biocontrol of fungal diseases

Gary W. Kirfman
Entotech, 1497 Drew Ave., Davis, California 95616, USA
— Microbial products

Daryl Klint
Calgary(Parks and Recreation Dept.), PO Box 2100, Calgary, Alberta T2P 2M5
— Biocontrol of urban pests and weeds

Twyla Kopas
Improvement District #6, Nanton, Alberta T0L 1R0
— Biocontrol of weeds

Harry Krehm
Research Program Service, Agriculture Canada, Research Branch, Room 2125, K.W. Neatby Building, C.E.F, Ottawa, Ontario K1A 0C6

David Kroeker
Calgary (Parks and Recreation Dept.), PO Box 2100, Calgary, Alberta T2P 2M5
— Biocontrol of urban pests and weeds

Ted Kuchnicki
Environment Canada, Pesticides Division, Commercial Chemicals Branch, Conservation and Protection, Ottawa, Ontario K1A 0H3
— Microbial control

Derek Lactin
Integrated Crop Management Inc., PO Box 164, Okanagan Centre, British Columbia V0H 1P0
— Agricultural entomology

Jack Laycraft
Calgary Parks and Recreation Dept., PO Box 2100, Calgary, Alberta T2P 2M5
— Biocontrol of urban pests and weeds

Shiyou Li
Queen's University, Department of Biology, Kingston, Ontario K7L 3N6
— Orchard pest management

Dan Lindgren
ICI Chipman, #6 2135-32 Ave. N.E., Calgary, Alberta

Tim Lysyk
Agriculture Canada, Research Station, PO Box 3000, Lethbridge, Alberta T1J 4B1
— Biocontrol of livestock pests

Roberte Makowski
Agriculture Canada, PO Box 440, Regina, Saskatchewan S4P 3A2
— Biocontrol of weeds with plant pathogens

Lynn Manaigre
Integrated Pest Management, 5 Alderwood Rd., Winnipeg, Manitoba R2J 2K7
— Biological control (interior plantscapes)

Peter G. Mason
Agriculture Canada, Research Station, 107 Science Crescent, Saskatoon, Saskatchewan S7N 0X2
— Biocontrol of insect pests on field crops and livestock

Jim Matteoni
Westgro Sales, Inc., 7333 Progress Way, Delta, British Columbia V4G 1E7
— Greenhouses, horticulture

Patrick Matthews
Calgary Parks and Recreation Dept., PO Box 2100, Calgary, Alberta T2P 2M5
— Biocontrol of urban pests and weeds

Alec McClay
Alberta Environmental Centre, Bag 4000, Vegreville, Alberta T0B 4L0
— Biocontrol of weeds

Catherine A. McCloskey
Dept. of Plant Science, Suite 248-2357 Main Mall, University of British Columbia, Vancouver, British Columbia V6T 2A2

Wendy McFadden
Horticulture Research Institute of Ontario, Vineland Station, Ontario L0R 2E0
— Integrated pest management in fruit

Bill McGregor
Dow-Elanco Canada Ltd., 9635 45 Avenue, Edmonton, Alberta T6E 5Z8
— Mycoherbicides, mycofungicides

John McIntosh
Canadian Parks Service, 520-220 4th Ave. S.E., Calgary, Alberta T2P 3H8
— Forest pest management

Malcolm McKee
University of Calgary, Biological Sciences, 2500 University Dr. N.W., Calgary, Alberta T2N 1N4
— Predator/prey interactions, mosquito biocontrol

Murray McLaughlin
Ag. West BioTech Inc., 105-15 Innovation Blvd., Saskatoon, Saskatchewan S7N 2X8
— All aspects of biotechnology

Rod McLeod
Gustafson Inc., #4 2216-27 Ave NE, Calgary, Alberta T2E 7A7
— Plant disease

Marlene McMann
Kootenay Livestock Association, PO Box 184, Cranbrook, British Columbia V1C 4H7
— Noxious weeds

Tim W. McMurray
City of Saskatoon, Pest Management, 1101 Ave P.N., Saskatoon, Saskatchewan S7L 7K6
— Urban pests, weed control

Nina Merchant
Alberta Research Council, PO Box 8330, Station 7, Edmonton, Alberta T6H 5X2
— General biocontrol

Tayyeba Mirza
The Professional Gardener Co. Ltd., 915-23 Ave. S.E., Calgary, Alberta T2G 1P1
— Microbiology, pests

Grant Moir
City of Red Deer, PO Box 356, Red Deer, Alberta T4N 5E9
— Biocontrol of mosquitoes, other insect pests and weeds

Keith C. Moore
Agriculture Canada Research Stn., 107 Science Cres., Saskatoon, Saskatchewan S7N 0X2
— Insect pathology

Nidia Moreno
University of Alberta, Department of Entomology, 2-27 Earth Sciences Building, University of Alberta Edmonton, Alberta T6G 2E3
— Biological control of field crop pests

Dean Morewood
University of Victoria, Department of Biology, PO Box 1700, Victoria, British Columbia V8W 2Y2
— Biocontrol of arthropod pests in agriculture and forestry

Knud Mortensen
Agriculture Canada, Research Station, PO Box 440, Regina, Saskatchewan S4P 3A2
— Biocontrol of weeds with plant pathogens

Barbra Mullin
Montana Dept. of Agriculture, 920 No. Benton, Helena, Montana 59601, USA

Bill Murray
Health and Welfare Canada, Bureau of Chemical Safety, Food Directorate, Sir Frederick Banting Bldg, Ottawa, Ontario K1A 0L2
— Safety assessment, food residues

Hannah Nadel
Royal British Columbia Museum, 675 Bellville Street, Victoria, British Columbia V8V 1X4
— Mass production of biocontrol agents, esp. parasitic hymenoptera

John Nerland
Agriculture Canada, Research Station, 107 Science Crescent, Saskatoon, Saskatachewan S7N 0X2
— Biocontrol of forage insect pests

Maria Neuwirth
Alberta Environmental Centre, Bag 4000, Vegreville, Alberta T0B 4L0
— Electron microscopy

Harriet Nicholls
Agriculture Canada, K.W. Neatby Building, 960 Carling Avenue, Ottawa, Ontario K1A 0C6

John T. O'Donovan
Alberta Environmental Centre, Bag 4000, Vegreville, Alberta T0B 4L0
— Biocontrol of aquatic vegetation

Michi Okuda
Alberta Agriculture, Regional Crops Lab, Olds, Alberta T0M 1P0
—Biocontrol of field crop insects

Craig Osterloh
Alberta Public Works, Supply and Services, Oldman River Dam Project Office, PO Box 1540, Pincher Creek, Alberta T0K 1W0
— Weed control, rangeland, trees/shrubs

David W. Owen
10305-81 St., Edmonton, Alberta T6A 3K8

Ian Pengelly
Banff National Park, Box 900, Banff, Alberta T0L 0C0
— Control of non-indigenous plants

Teresa Perry
Calgary Parks and Recreation Dept., PO Box 2100, Calgary, Alberta T2P 2M5
— Biocontrol of urban pests and weeds

Diether Peschken
Research Station, Agriculture Canada, PO Box 440, Regina, Saskatchewan S4P 3A2
— Biocontrol of weeds

Hugh Philip
Ministry of Agriculture and Fisheries, 1873 Spall Road, Kelowna, British Columbia V1Y 4R2
— Extension entomology, agriculture

Donna Pickle
Crop Protection Branch, Alberta Agriculture, 7000-113 Street, Edmonton, Alberta T6H 5T6
— General biocontrol

Ken Pivnick
Agriculture Canada, Research Station, 107 Science Cres., Saskatoon, Saskatchewan S7N 0X2
— Canola entomology

Rob Powell
University of Alberta, Botany Department, Edmonton, Alberta
— Biocontrol of weeds

Raoul Powlowski
Integrated Crop Management Inc., PO Box 164, Okanagan Centre, British Columbia V0H 1P0
— Agriculture entomology

Geraldine Quin
University of Calgary, 2500 University Dr. N.W., Calgary, Alberta
— IPM

Fayyaz A. Qureshi
Alberta Environmental Centre, Bag 4000, Vegreville, Alberta T0B 4L0

Rod Raphael
Health and Welfare Canada, Pesticides Division,, Health Protection Branch, Rm 1505 Brooke Claxton Bldg., Tunney's Pasture, Ottawa, Ontario K1A 0K9
— Human health and safety involving microbial pesticides

M.S. Reddy
Esso Ag Biologicals, Suite # 402, 15 Innovation Boulevard, Saskatoon, Saskatchewan S7N 2X8
— Biocontrol of plant diseases

Jens Roland
University of Alberta, Edmonton, Alberta T6G 2H7
— Biocontrol of insects, population dynamics, chemical ecology

Don Ross
City of Saskatoon, Pest Management, 1101 Ave P.N., Saskatoon, Saskatchewan S7L 7K6
— Urban pests, insects, weed control

Michael Sarazin
Biosystematics Research Centre, K.W. Neatby Bldg., Central Experimental Farm, Ottawa, Ontario K1A 0C6
— Importations, rearing, quarantine, news for "Biocontrol News"

Anita M. Schill
Olds College, Olds, Alberta T0M 1P0

Diane Schneider
Westgro Horticultural Supplies Inc., 4310-12 St. S.E., Calgary, Alberta T2G 3H9
— Greenhouse biologicals

Wendy A. Sexsmith
Department of the Environment, PO Box 6000, Fredrickton, New Brunswick E3B 5H1
— Regulation

Simon F. Shamoun
Forestry Canada, Pacific Forest Centre, 506 West Burnside Road, Victoria, British Columbia V8Z 1M5
— Biocontrol of weeds, mycoherbicides

M. Paul Sharma
Alberta Environmental Centre, Bag 4000, Vegreville, Alberta T0B 4L0
— Weed management, pest management

Jerry Shaw
Agriculture Canada, Room 815, 9700 Jasper Ave., Edmonton, Alberta T5J 4G4
— Biocontrol of plant diseases

Jeff Sheedy
Mount Royal College, Biology Dept., 4825 Richard Rd. Sw, Calgary, Alberta T3E 6K6
— Biological pest control in greenhouses

J. Shemanchuk
Agriculture Canada, Research Station, PO Box 3000, Lethbridge, Alberta T1J 4B1
— Biocontrol of urban and domestic pests

Jerry Shyluk
National Research Council, Plant Biotechnology Institute, 110 Gymnasium Road, Saskatoon, Saskatchewan S7N 0W9
— Biocontrol in greenhouses

Dale Silbernagel
Calgary Parks and Recreation Dept., PO Box 2100, Calgary, Alberta T2P 2M5
— Biocontrol of urban pests and weeds

Steve Slopek
Crop Protection Branch, Alberta Agriculture, 7000-113 Street, Edmonton, Alberta T6H 5T6
— General biocontrol

Kathy Smalko-Billings
Calgary Parks and Recreation Dept., PO Box 2100, Calgary, Alberta T2P 2M5
— Biocontrol of urban pests and weeds

Risa Smith
Vedalia Biological Research, R.R.#2, Porlier Pass Road, Galiano, British Columbia V0N 1P0
— Biocontrol of insects

Sandy Smith
University of Toronto, Faculty of Forestry, 33 Willcocks Street, Toronto, Ontario M5S 3B3
— Biocontrol of forest insects

Calvin Sonntag
Hoechst Canada Inc., 1024 Winnipeg Street, Regina, Saskatchewan S4R 8P8
— Biocontrol of weeds, field crop insect pests

Julie Soroka
Agriculture Canada, Research Station, 107 Science Crescent, Saskatoon, Saskatchewan S7N 0X2
— Biocontrol of forage insect pests

Larry Speers
Agriculture Canada BRC, K.W. Neatby C.E.F., Ottawa, Ontario K1A 0C6
— Biosystematics

Dale Spiers
Calgary Parks and Recreation Dept., PO Box 2100, Calgary, Alberta T2P 2M5
— Biocontrol of urban pests and weeds

Marilyn Steiner
Alberta Environmental Centre, PO Bag 4000, Vegreville, Alberta T0B 4L0
— Greenhouse biocontrol

Bill Stewart
Grains and Oilseeds Branch, Agriculture Canada, Sir John Carling Bldg., Room 1035, 930 Carling Ave., Ottawa, Ontario K1A 0C5
— Microbial control agents

Norman Storch
Alberta Agricultural Research Institute, PO Box 1358, Hanna, Alberta T0J 1P0
— Conservation

Allen Sturko
Ministry of Forests, 3015 Ord Road, Kamloops, British Columbia V2B 8A9
— Biocontrol of weeds

Jon Sweeney
Forestry Canada – Maritimes Region, P.O. Box 4000, Fredericton, New Brunswick E3B 5P7
— Forest pests, nematodes

Arthur Tellier
Alberta Special Crops and Horticultural Research Centre, PO Bag 200, Brooks, Alberta T0J 0J0

Norman Temple
Alberta Environmental Centre, Bag 4000, Vegreville, Alberta T0B 4L0
— Spores

Gina Townsend
The Professional Gardener Co., 915-23 Ave. S.E., Calgary, Alberta T2G 1P1
— Pest control

Bill Turnock
Agriculture Canada, Research Station, 195 Dafoe Rd., Winnipeg, Manitoba R3T 2M9
— Biocontrol of insect pests of field crops

Barry Tyler
Abbot Laboratories Ltd., R.R. #1, Orton, Ontario L0N 1N0
— Potential of biocontrol in Canada, issues affecting progress

Nick Underwood
Canola Council, 301-433 Main Street, Winnipeg, Manitoba R3B 1B3
— Crop production: canola

John Van den Broeke
County of Lethbridge, 905-4th Ave. South, Lethbridge, Alberta T1J 4E4
— Weed control

Roy Van Driesche
Dept. of Entomology, University of Massachusetts, Amherst, Massachusetts 01003, USA
— Coordination in biocontrol

Casey Van Teeling
Alberta Environment, 5th Floor 9820-106 Street, Edmonton, Alberta T5K 2J6
— Biocontrol of pests

Rina Varma
Alberta Environmental Centre, Bag 4000, Vegreville, Alberta T0B 4L0
— Biocontrol of weeds with plant pathogens

Charles Vincent
Station de Recherches, Agriculture Canada, 430 Boul. Govin, St. Jean-sur-Richelieu, Québec J3B 3E6
— Agriculture, IPM

Betty Vladicka
Alberta Tree Nursery and Horticulture Centre, R.R. 6, Edmonton, Alberta T5B 4K3
— Greenhouse crops, trees, ornamentals

Jeff Waage
Deputy Director, CAB International Institute of Biological Control, Silwood Park, Buckhurst Road, Ascot, Berks. SL5 7TA, UK

Sandy Walde
Dalhousie University, Department of Biology, Halifax, Nova Scotia B3H 4J1
— Orchard pest control, European red mite

Don Wallace
Forestry Canada, PO Box 490, Sault Ste. Marie, Ontario P6A 5M7
— Importation and propagation of biocontrol agents, *Trichogramma* propagation, diprionid sawflies.

K.F. Weiss
Bureau of Microbial Hazards, Health Protection Branch, H.N. Banting Research Centre, Ross Avenue, Ottawa, Ontario K1A 0L2
— Regulation and safety assessment

Brian Weller
Canadian Parks Service, Ottawa, Ontario K1A 0H3

Gordon Wells
Tradex International Consulting Corp., South Tower, Sun Life Plaza, Suite 1100, 144-4 Avenue S.W., Calgary, Alberta T2P 3N4
— Pest biocontrol in oilseeds

William Westlin
Municipal District of Brazeau, PO Box 77, Drayton Valley, Alberta T0E 0M0

Dave Whitehead
Biosafe Horticulture Services, 517 Victoria Avenue, Victoria, British Columbia V8S 4M8
— Urban biocontrol

Richard Winder
Dept. of Plant Science, McGill University, Ste. Anne-de-Bellevue, Québec H9X 1C0
— Weed control with mycoherbicides

Ian Wise
Agriculture Canada, Research Station, 195 Dafoe Rd., Winnipeg, Manitoba R3T 2M9

Fred Wrona
University of Calgary, Biological Sciences, 2500 University Drive N.W., Calgary, Alberta T2N 1N4
— Mosquito biocontrol

Walter Yarish
Crop Protection Branch, Alberta Agriculture, 7000-113 Street, Edmonton, Alberta T6H 5T6
— General biocontrol

Piao Yongfan
W.U.S.C., c/o Jeanette Stovel, PO Box 3000, Station C, Ottawa, Ontario K1Y 4M8