4.0 SUMMARY AND PROSPECTS FOR THE FUTURE

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SUMMARY

We report the results of a 5-year project to develop the technology of mass-production and inundative release of *Trichogramma minutum* Riley against the eastern spruce budworm, *Choristoneura fumiferana* (Clemens).

Techniques were developed to produce 30×10^6 *T. minutum* per week on the factitious host *Sitotroga cerealella* (Olivier). To facilitate shipment and aerial release in spruce budworm-infested forests, *Trichogramma* development was programmed so that parasitoids emerged from their hosts within 24 h of exposure after release.

Test sites for the release of *T. minutum* were selected on the basis of suitably high densities of spruce budworm, projected stability of the pest population, uniform size of host trees (especially white spruce), low levels of parasitism by natural populations of *T. minutum*, and ease of access. An area of Rogers Township, north of Hearst, Ont., fulfilled these requirements.

Aerial release of parasitized host eggs was successfully achieved with a Bell® 47 helicopter, equipped with a Brohm aerial seeder, modified to deliver parasitized eggs over an effective swath width of ca. 10 m. During the 5 years of releases, application rates varied between 0.6×10^6 and 25.0×10^6 ♀♀ parasitoids per hectare. Sticky cards were used to measure distribution of the parasitized host eggs within the stand. More than 50% of the released material reached ground level. Horizontal distribution within the plots was uneven, with more parasitoids deposited in the centre than at the edges. Horizontal drift was usually less than 25 m from the flight path, and never exceeded 100 m; maximum wind speed during the applications was >5 km/h. Characteristics of the parasitoids, measured as percentage emergence, sex ratio, longevity, and fecundity, were not affected by aerial release.

Two systems for ground release of *Trichogramma* were developed for use on small plots: a gridded point source system, using parasitized host eggs attached to cards; and a hand-held leafblower for distributing eggs in bulk. Neither system affected the quality of the parasitoids and both resulted in rates of parasitism of sentinel egg masses similar to those obtained with aerial release. Parasitism was higher in the mid- to upper crown than in the lower crown of the trees.

The ability of varying rates of *T. minutum* releases to suppress an epidemic population of spruce budworm was assessed from 1982 to 1986. Parasitism was monitored using both naturally occurring and sentinel (laboratory-reared) egg masses of spruce budworm. The best results were achieved in 1984, with two releases, 6–7 days apart, at a total release rate of 22.7×10^6 ♀♀ parasitoids per hectare. These releases produced egg parasitism levels of over 80% on both balsam fir and spruce and subsequent reductions in larval populations of over 80%. Lower release rates and single releases were not as effective, although rates of ca. 8×10^6 ♀♀ parasitoids per hectare usually resulted in more than 60% egg parasitism.

The onset of oviposition by spruce budworm was predicted using the following: a regression model incorporating larval development; pheromone trap catches of male moths; sampling of egg masses on branches; and emergence of adult spruce budworm in a field laboratory. This was essential for the correct timing of parasitoid releases and subsequent optimization of parasitism.

By varying the release rate of *Trichogramma* from 4×10^6 to 29×10^6 ♀♀ per hectare, a curvilinear relationship between release rate and parasitism level was developed. This relationship indicates that parasitism levels of 60% can be achieved with a double release of 4×10^6 ♀♀ per hectare, and that over 80% parasitism will result from a double release of 10×10^6 ♀♀ per hectare. Higher application rates provided very little incremental benefit. Previous studies using double releases of 60 000 and 120 000 ♀♀ per hectare (Smith 1985) and 24×10^6 ♀♀ per hectare (Smith *et al.* 1987) support this relationship.

The present study has shown that spruce budworm egg parasitism can result in a subsequent reduction in mature larval populations. Larval reductions were proportional to parasitoid release rates, with rates of $8–23 \times 10^6$ ♀♀ per hectare resulting in a 42–83% reduction in larval densities the following year. A parasitoid release of 23×10^6 ♀♀ per hectare, followed by one application of *Bacillus thuringiensis kurstaki* Berliner (*B.t.k.*) the following spring, reduced larval populations by 93%. To develop recommendations for the use of *Trichogramma* against the spruce budworm, however, further research is needed to determine more precisely the relationship between egg mass parasitism and larval reduction.

In general, stand species composition had little effect on the percentage parasitism of spruce budworm eggs, but parasitism was somewhat higher on balsam fir than on white spruce. No carryover effect in parasitism from year to year was detected during the study. The density of spruce budworm eggs in the plots did not affect levels of parasitism by *T. minutum*; the abundance of eggs appeared to be less important than their temporal availability.

Weather conditions immediately following release affected the efficacy of parasitoids; cool, wet weather reduced and extended parasitoid emergence, with subsequent reductions in levels of parasitism.

Most important to the success of the releases was parasitoid quality. Proper methods of production, programming, and shipment were essential to obtain parasitoids of high quality and minimize the number of runted, ineffective individuals released. Efficacy in the field was directly proportional to parasitoid quality, as indicated by percentage emergence, longevity, and fecundity.

Prospects for the Future

Potential for Use in Forest Management

In the past decade, forest pest control technology in Canada has been steadily weakened through the loss of registered chemical pesticides and the stagnation of development and registration of new control products. These trends are unlikely to change in the near future. Public opposition to the use of chemical pesticides in the forest environment is now well established (Paul 1988); it will likely continue and expand to include the newer generations of pesticides, e.g. insect growth regulators, pheromones, and perhaps even commercial formulations of *B.t.k.* Yet the need for cost-effective control technology is increasing as investment in forest renewal continues to rise and insect-caused losses to industrial wood supplies become less tolerable. New insect control agents are urgently needed to fill the widening technology gap, and for many reasons, scientific and social, the tactic of inundative release of insect parasitoids, such as *T. minutum*, has considerable promise.

Operational control programs against forest defoliators are undertaken for one of three purposes: control of outbreaks; containment of outbreaks; or foliage protection. *Trichogramma minutum* has the potential to serve an important role in all three. This study has shown that double applications of *Trichogramma* (when used alone or sequentially with *B.t.k.*) at the rate of $10–12 \times 10^6$ ♀♀ per hectare can reduce larval population levels by over 80% and that population levels could be reduced sufficiently to control or contain an outbreak of eastern spruce budworm.

Current foliage protection objectives for operational spraying against spruce budworm require that 50% of the current year's growth be preserved on spruce, and 60% on balsam fir. Defoliation levels greater than 50% can be expected if the population density exceeds 377 eggs per square metre of foliage during the previous year (Dorais and Kettela 1982). Thus, any technology that can consistently reduce egg densities below 377 per square metre has the potential to provide adequate foliage protection against spruce budworm, by current standards. Clearly, the use of *T. minutum* has that potential and, furthermore, adequate protection may be achievable with release rates lower than $10–12 \times 10^6$ ♀♀ per hectare.

Apart from the potential of this technology against eastern spruce budworm, there are other forests and other pests for which *T. minutum* may be useful. Because of government regulations and public opposition, there are many forest situations in which the use of chemical insecticides is not possible. These include "no spray" zones around human habitation, drinking water supplies, aquatic habitat, and public recreation areas. In some provinces, these zones affect large areas of productive forest land, and effectively exclude them from protection. In such zones, the use of *T. minutum* would be an acceptable option. As well, there are categories of high value forests that are intensively managed and require a high level of protection, because of product value or social value — seed orchards, tree nurseries, Christmas tree plantations, urban forests, and parks. Because chemicals may be difficult or impossible to use in these situations, *Trichogramma* could serve as an effective and acceptable option.

The present research has been restricted to eastern spruce budworm, but there are other forest pests that are parasitized naturally by *Trichogramma* and may be good candidates for this technology: spruce budmoth, *Zeiraphara canadensis* Mutuura and Freeman; western spruce budworm, *C. occidentalis* Freeman; jack pine budworm, *C. pinus pinus* Freeman; eastern hemlock looper, *Lambdina fiscellaria* (Guenée); black army cutworm, *Actebia fennica* (Tauscher); and several insect pests of coniferous seeds and cones.

Future Research

Trichogramma minutum are biologically active control agents capable of searching out and killing host eggs, and when used in inundative releases against spruce budworm, they can suppress outbreak populations. From the present study, it is clear that the release of *Trichogramma* against forest insect pests is biologically and technologically feasible. The future direction of this biological approach to forest pest management, however, lies in its commercialization.

Commercialization means developing the technology to optimize the mass-rearing of *Trichogramma* and expanding its use against several insect pests. In this context, three key areas for future research can be identified:

(1) the development of a cost-effective rearing system;
(2) the characterization and improvement of parasitoid quality; and
(3) the refinement of a release strategy for optimal efficacy in the field.

Cost-effective rearing: Operational use of *Trichogramma* will require the technology to consistently mass-rear large numbers of high quality parasitoids on a continual basis. Many of the natural hosts of *Trichogramma*, including the spruce budworm, the bollworm, *Heliothis zea* (Boddie), and the European corn borer, *Ostrinia nubilalis* (Hubner), are difficult or expensive to rear and, as a result, alternative hosts have been found for cheaper, easier mass-rearing (Morrison 1976). Lepidopterous species infesting stored products have proven to be very suitable hosts, e.g. the Angoumois grain moth, *Sitotroga cerealella*

(Olivier), and are currently the sole means of commerical production in other countries. Although research is now underway in the United States, Canada, and China to investigate the potential for mass-rearing *Trichogramma* on artificial diets, this approach is not yet commercially feasible.

The development of efficient mass-rearing technology is the key factor for commercial success. To make *Trichogramma* commercially viable and competitive with current control agents (*B.t.k.*), production costs will have to be in the order of \$10–\$20.00 per hectare. The experimental production unit developed in the present study, at the University of Guelph, currently uses the Angoumois grain moth as the rearing host and has a capacity of 35×10^6 parasitoids per week. To achieve the desired economy of scale, production would have to be increased up to $>200 \times 10^6$ parasitoids per week (or $>100 \times 10^6$ ♀♀ parasitoids per week).

Increased output and reduced costs can be achieved by automating the production system in two ways. First, the amount of manual labour in the rearing system will have to be reduced by introducing mechanically engineered designs into the system. The relatively high amount of handling in the current system is the primary cost factor in production. Second, the rearing of the parasitoid system will have to be disassociated eventually from its dependence on the rearing of the host system. This will serve to improve human health and safety standards by reducing the amount of moth scales during mass-rearing as well as enhance the reliability of the system when host eggs can either be stored in a suspended state for long periods of time or completely replaced with artificial eggs. This will eventually lead to increased outputs and reduced costs due to an improved economy of scale.

Parasitoid quality: To ensure consistent field efficacy and, thus, cost-effectiveness, any automated rearing system will have to be capable of producing *Trichogramma* of high quality. In China, a rearing technique has been developed to ensure that the parasitoids must fly to the host eggs to oviposit (Li 1983). Similarly, Bigler *et al.* (1987) maintained a high quality parasitoid by ensuring flight during mass-rearing. Although this approach contributes to higher parasitoid quality, it is extremely labour intensive and not suited to commercialization. Recently, in the southern United States, Morrison (1976, 1986) developed a continuous rearing system on Angoumois grain moth eggs; however, to date, no continuous quality control of parasitoids reared in this system has been implemented.

The maintenance of high quality *Trichogramma* during mass-rearing will require research to determine the optimal rearing conditions for both the parasitoid and host, as well as the effect of varying conditions of programming, cold storage, and shipping. Clearly, to be cost-efficient in Canada, large numbers of *Trichogramma* must be stored for extended periods to stockpile quantities during the winter for release in the active field season (April to September). It is important, therefore, that we develop techniques for cold storage (or other conditions of mass-rearing) that do not significantly reduce the quality of the parasitoids.

Parasitoids of "high quality" are those with biological attributes that contribute to high levels of parasitism in the field (Manweiler 1986; Pak 1986; Pak *et al.* 1986; Vinson 1976). Intuitively, for Canada, this means *Trichogramma* with the following characteristics: (1) good flying ability; (2) good host searching ability; (3) selective host specificity (host discrimination); (4) high intrinsic rate of increase; (5) good tolerance to low temperatures; and (6) acceptability of small hosts for rearing.

Of considerable importance to the success of future commercialization will be the development of a technique for identifying high quality or superior strains of *Trichogramma*. Previous experiments have shown that isozyme patterns are well suited to detecting differences in strains of *T. minutum* (Smith and Hubbes 1986*a*, 1986*b*). Studies should be continued in this area to identify biochemical markers that are characteristic of parasitoid strains and indicative of changes in parasitic biology during rearing.

To improve parasitoid quality, it will first be necessary to identify those biological attributes that are correlated with and can predict efficacy in the field (Boller 1979). Once these have been established, continued research can determine whether such attributes are linked to genetic components and, thus, are capable of being improved through selective breeding and/or biotechnological manipulation (Whitten 1979, 1986; Roush 1979).

Optimal field efficacy: To optimize the field efficacy of *Trichogramma*, two different research directions must be taken. The first will improve our understanding of the relationship and impact of *Trichogramma* on spruce budworm populations. The best release regimen or tactics, in terms of the number of releases, the number of parasitoids per release, and the timing of single or double releases, must be established. As well, we should improve our understanding of the effect of host density and distribution on the functional response of the parasitoid, as well as the effect of stand attributes on egg parasitism. Finally, it is important that we obtain baseline information on the potential for integrating *Trichogramma* releases with other control options such as *B.t.k.*

This proposed research could be advanced effectively through the development and use of simulation models similar to those utilized in agriculture (Knipling and McGuire 1968). Modelling, although no substitute for field releases, would reduce the relatively high costs of such field assessments by quickly identifying the most promising strategies. In this way, experimental studies could be targeted more precisely to critical questions.

The second avenue of research should be the identification of other insect pests and situations for which *Trichogramma* will be well suited as a management technique. We have noted that a number of forest insect pests in Canada can be attacked by species of *Trichogramma*. Investigations should address the potential for using inundative releases of such parasitoids to suppress these forest pests. This will entail studies to determine acceptability and availability of the various host species as well as the impact of parasitoid releases on pest populations.

Trichogramma minutum is the one North American species of this genus with proven effectiveness against the spruce budworm and the one currently being mass-reared at Guelph. There are a number of other species of *Trichogramma*, however, that attack forest defoliators in the United States, Europe, and China, including *T. embryophagum* (Htg.), *T. cacoecia* Marchal, *T. dendrolimi* (Matsumura), and *T. zeirapherae* Walter on forest pests such as *Dendrolimus* spp., *Zeiraphera diniana* Guenée, *Dioryctria* spp., and *Rhyacionia* spp. (Mills *et al.* 1986; Walter 1985; Belmont and Habeck 1983; Hsiao 1981; Tsankov *et al.* 1980). The potential of these parasitoids, as well as any unknown species or possible ecological strains within each species, should be explored in the prospect that they will be of better "quality" than *T. minutum* for release.

Conclusion

Successful research on cost-effective rearing, parasitoid quality, and field efficacy will expedite the commercialization of *Trichogramma* for the control of insect pests. Although this research has been directed at spruce budworm, a much broader application is anticipated with continued research and development of the technology. If we are successful in commercially producing and utilizing mass-reared parasitoids, this will have a significant impact on the way we manage insect pests in the forest environment. This technology has great potential for use as a replacement for conventional pesticides and as an agent that is compatible with microbial insecticides and silvicultural techniques. Clearly, it can play a key role in the integrated management of forest pests.

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