PN-ABK-367
6.133

STATUS OF THE BIOLOGICAL CONTROL OF PESTS

David Pimentel[1] and Martha S. Hunter[2]

Paper for:
EVOLUTIONARY TRENDS IN PLANTS
1/14/92

[1]Dept. of Entomology, Comstock Hall, Cornell University, Ithaca, NY 14853
[2]Dept. of Biol. Imperial College at Silwood Park, Ascot, Berks. SL5 7PY, UK

STATUS OF THE BIOLOGICAL CONTROL OF PESTS

INTRODUCTION

Plant, insect and pathogen populations in nature are often controlled by natural enemies (predators, parasites and competitors). Complexes of natural enemies are also present in agricultural systems, and have been estimated to consume 50% of pest populations (Pimentel et al. 1992a). The common phenomenon of "resurgence" in which chemical pesticides remove natural enemies and exacerbate rather than relieve pest problems illustrates the importance of natural control in agroecosystems.

Biological control involves the manipulation of natural enemies to control pests. It seeks to enhance the impact of naturally-occurring enemy species by enriching the habitat ("conservation"), restoring an existing enemy-pest relationship in a new area ("classical biological control"), or pairing enemies in new associations with pests ("new associations biological control").

Natural enemies may be conserved by improving the structural or biological diversity of agroecosystems in ways designed to attract and keep them in the system. An example is the recent use of "mini-hedgerows", raised strips of vegetation parallel to rows of crops in cereal fields (Thomas et al. 1991). These strips provide overwintering sites and nectar sources for generalist predators such as staphylinid and carabid beetles. The cost of planting and maintaining these strips has been shown to be more than compensated by savings in pesticide applications and crop loss (van Emden 1990). Classical biological control involves the restoration of the interaction between natural enemies and pest in a new habitat following the accidental

introduction of the pest. Generally ecologists search the area of origin of the pest for its natural enemy complex, and introduce those species that are sufficiently specific in the range of prey or hosts they attack. Another approach is to look for a natural enemy attacking a species related to the target pest. This "new association" approach increases the potential area of search to all climatically-suitable areas where relatives of the pest occur.

Effective biological control has many advantages over the use of chemical pesticides. First and foremost, biological control agents have a restricted diet, and with few exceptions, attack only the target pests. Unlike broad-spectrum pesticides, biological control agents do not poison humans, birds, fish, and other wildlife, nor do they destroy non-target beneficial natural enemies as may pesticides (Pimentel et al. 1992a). In general, biological control agents maintain and even improve the overall quality of the environment, thus conserving biological diversity.

In the following, several aspects of the status of biological control are discussed, including: the choice of a biological control agent, economic benefits, the role of biological control in conservation of biological diversity, and the future of biological control. Although conservation of natural enemies is an area of increasing interest and importance, we will restrict our discussion to biological control introductions.

CHOICE OF A BIOLOGICAL CONTROL AGENT

The choice of a natural enemy is critical in determining the success or failure of a biological control program, but there is still very little predictability about the outcome of any particular introduction. Agents are often introduced on a trial-and-error basis and biological control introductions often fail. Natural enemies may not become established, or if they establish they may not have an

appreciable effect on the pest population. For example, none of the 26 species of parasitoids and predators introduced into Canada to control the European corn borer (*Ostrinia nubilalis*) have exerted appreciable control (Clausen 1978, Turnock 1991). In addition, in more than 95% of the cases of successful biological control, a single species of natural enemy has been responsible for the success (Sweetman 1958, DeBach 1964, Huffaker et al. 1971, Zwölfer et al. 1976, Huffaker 1980).

The lack of predictability in determining which agents will succeed and which will fail is partly due to lack of information about the biology of the agents. Gathering extensive knowledge of the life history of the agents, however, may be prohibitively expensive for a biological control program with a limited budget. No matter how sophisticated our understanding of the interactions between natural enemies and their victims becomes, the complexity of natural systems is likely to continue to prove some predictions wrong. A recent case in point is the New Zealand biological control program for a weevil pest of lucerne. A parasitic wasp was introduced from Australia where the wasp is well synchronized with the weevil phenology. Wasps parasitize adult weevils as they emerge in the spring, and travel with the weevils out of the lucerne fields to aestivating sites as non-developing first instar larvae (Goldson *et al.* 1990). In New Zealand, however, about 3% of the parasitized weevils do not leave the fields, and the wasps in these hosts complete development and in turn parasitize many of the remaining weevils as they emerge, leading to a very high percentage of parasitism in the aestivating weevils (Goldson *et al.* 1990). This unexpected and "atypical" behavior, affecting only a small portion of the population, is probably the reason for dramatic success in control of the weevil in New Zealand (Goldson *et al.* 1990).

Another decision that must be made in choosing a biological control agent is the location of the search. In classical biological control, exploration for natural enemies is generally conducted in the place of origin of the pest, and natural enemies selected that are found attacking the pest. In the new associations approach, natural enemies are chosen that have not evolved with the pest but attack close relatives wherever they occur in the world. The objective of the new associations approach is to take advantage of the lack of evolved balance common to natural parasite-host systems (Pimentel 1963, Dennill and Hokkanen 1990). In addition, consideration of natural enemies of related pests as well as the target pest increases the number of possible species that are available for biological control agents. It also broadens the range to include both introduced and native species as targets for biological control. Note, most pest species, especially insects, are native species that became pests (Pimentel, 1986). The relative merits of the two approaches have been the subject of vigorous debate in the literature, and the relative success rate of the two methods varies with the analysis and database (Hokkanen and Pimentel 1984,1989, Waage 1990). In general, both new and old associations have an important role in biological control. Indeed, many of the spectacular biological control successes have been implemented with new associations (Turnock et al. 1976, Drooz et al. 1977, Briggs 1986, Legner 1986, Cock and Perera 1986, Ehler 1987, Miller et al. 1987, Lawton, 1988, Moser and Branham 1988, Dennill and Moran 1989, Hokkanen and Pimentel 1989, Oka et al., 1991).

ECONOMICS

Many economic benefits result from the successful control of pests by introduced biological control agents. Natural enemies are self-perpetuating,

and respond to pest increases through increased reproduction of their own. Thus once established, they function without further investment or attention.

While the costs of biological control accrue only until the time a successful agent is released and evaluated, the economic benefits continue to accumulate for as long as the pest is effectively controlled. The benefits can be measured in terms of the savings in crop production, and in savings in alternative pest controls such as pesticides as well as in benefits to consumers of lower prices resulting from increased supply (Tisdell 1990). Since the Vedalia beetle became established in California, it has provided effective control of the cottony-cushion scale of citrus without any further investment. The initial investment to introduce the beetle from Australia was about $5,000. Since1892, the beetle has saved the citrus industry $10-$15 million each year. Thus the return per dollar invested in biological control has been about $200,000 per year without calculating interest on the return on the investment for the past 100 years.

An analysis of investment in research by Australia's CSIRO Division of Entomology showed a cost/benefit ratio of 32:1 for biological research versus 2.5:1 for non-biological pest control research (Tisdell 1990). In the United States most biological control agents return $30 to $100 for every dollar invested (PSAC 1965, Huffaker et al. 1976). This is in contrast to most pesticides that return $2 to $4 for every dollar invested (Pimentel et al. 1992a).

ROLE OF BIOLOGICAL CONTROL AGENTS IN CONSERVATION OF DIVERSITY

The aim of biological control is to introduce an agent that attacks the target pest, but otherwise has little impact on the environment. In the 100 years of modern biological control this aim has been achieved with few exceptions.

There are two reasons for this success. First, natural enemies with a restricted diet are common. Parasitic wasps, for example, generally attack only a few closely related species of insects. Secondly, efforts have been made to choose only those natural enemies that are specific to the pest. This practice is most highly developed in the biological control of weeds, where prior to introduction, agents are rigorously tested against both wild and cultivated relatives of the target pest (Wapshere et al. 1989). Thus, the contrast between the specificity of biological control agents and broad-spectrum pesticides is great.

Pesticide use in crops destroys natural enemies, birds, mammals, fishes, and non-target plants. The estimated environmental impact in the United States from recommended pesticide use has been estimated to be $8 billion each year (Pimentel et al. 1992a). The destruction of natural enemies is estimated to cost agriculture $520 million annually in added pesticides and increased crop losses. The recommended use of certain herbicides may make crop plants more susceptible to pest attack. For example, when corn was treated with the recommended dose of the herbicide 2,4-D, the corn crop was significantly more susceptible to two insect and two plant pathogen pests (Oka and Pimentel 1976).

A recent critique of the practice of biological control introductions suggests that the scarcity of evidence for negative impacts of control agents (introduced by trained ecologists) on indigenous flora and fauna is due to lack of study (Howarth 1991). However, even a relatively anthropocentric view of the environmental impacts of exotic pests has revealed several extinctions and untold environmental destruction. An example is the weed purple loosestrife, which is endangering two plant species, and causing a decline of a turtle species and the black tern in North America (Thompson et al. 1987). The point is not that biological control agents never have negative impacts on the

environment, but that risk assessments must balance the environmental impact of an introduced pest (that is , the consequences of doing nothing) with that of a host-specific natural enemy (Harris 1990).

Ecological disasters have resulted, however, when untrained individuals have introduced control agents. Notorious examples are the introductions of the giant cane toad and Indian mongoose to several areas of the world where they have become a noxious pests (Pimentel et al., 1984, Floyd and Easteal 1986). These catastrophes highlight the ongoing need for strict monitoring of biological introductions worldwide to prevent action by amateur 'vigilante' ecologists.

FUTURE

The bright future of biological control seems assured. It is ecologically sound, inexpensive and is likely to be an integral part of future pest management. Several areas of biological control are becoming more important; here, we mention the use of pathogens, and the incorporation of ecological and evolutionary theory into the science of biological control.

Plant pathogens have become both the targets of biological control, as well as agents to control weeds. Plant growth-promoting rhizobacteria are now being used to combat soil-borne pathogens (Reddy 1991). These bacteria suppress pathogens with toxins or through parasitism, competition or induction of resistance in the plant (Reddy 1991). As biological control agents of weeds, plant pathogens have been shown to be effective and highly specific; an example is the rust introduced to attack skeleton weed in Australia (Wapshere et al. 1989).

One of the fastest growing areas in biological control is the use of insect pathogens as 'biopesticides'. The advantage of these over synthetic pesticides

is their specificity - harm to non-target organisms is minimized. Currently, target-specific strains of the bacteria *Bacillus thuringiensis* (BT) are the subject of major development. Sprays of this bacteria are applied like pesticides; the bacteria break down rapidly in the environment and little transmission of the bacteria occurs from one insect to another. To increase the persistence of the bacteria, *B.t.* toxin genes have been incorporated in crop plants where they are expressed, and poison the target pest upon consumption. Perhaps one of the greatest concerns in the use of these products is the development of pest resistance - relatively few organisms have been developed in this manner and few alternatives are available if they fail (Gould 1988, Pimentel et al. 1989). Recently resistance to BT developed in Southeast Asia when farmers used it as a replacement for broad-spectrum pesticides in calendar-spraying programs (Waage 1992).

Ecological and evolutionary studies of natural enemies, insect parasitoids in particular, have the potential to influence the practice of biological control. Although the theoretical basis of insect biological control is that populations are regulated by natural enemies, the source of stability in the interaction between parasitoid and host has been the subject of vigorous debate. Recent progress has been made in understanding how spatial heterogeneity in the pattern of attack by parasitoids may cause stability in the interaction (Pacala et al. 1990) and provides an explicit hypothesis with which biological control programs can be analyzed.

Evolutionary theory and the study of behavior has been slow to influence biological control, although the idea that the interaction between parasitoid and host is dynamic in an evolutionary sense is not new (Pimentel 1963). More recently the need to understand variation "within and between individuals" has been recognized (Roitberg 1990). Current study on the role of learning host-

associated chemical cues by parasitoids is likely to lead to effective manipulation of their behaviour when released in augmentation programs (Lewis and Martin 1990). Furthermore, while population genetics was introduced to solve laboratory-rearing problems in biological control it is now being used to understand the genetics of colonization (Roush 1990), and the variation in susceptibility to attack by parasitoids (Bouletreau 1986).

In conclusion, many opportunities exist to employ biological control for the many pests that occur in agriculture today. Biological control offers outstanding economic returns, and equally important, it can improve and protect the environment by conserving biological diversity in agricultural and natural ecosystems (Pimentel et al. 1992b).

ACKNOWLEDGEMENTS

This research was supported in part under grant no. 6.133, Program in Science and Technology Cooperation, USAID.

REFERENCES

Bouletreau, M., 1986. The genetic and coevolutionary interactions between parasitoids and their hosts. pp. 169-200. In Waage, J. and Greathead, D. (eds). Insect Parasitoids. Academic Press: London.

Briggs, J.D., 1986. Microbial control of arthropods. In Biological Plant Health Protection. Edited by J. M. Franz. 155-166. Stuttgart: Gustav Fischer Verlag.

Clausen, C.P., 1978. Introduced Parasites and Predators of Arthropod Pests and Weeds: A World Review. Washington, DC: U.S. Dept. of Agric., USDA Handbook 480.

Cock, M.J.W., and Perera, P.A.C.R., 1986. Biological control of Opisina arenosella. Biocontrol News Information 8 : 283-310.

DeBach, P.H., 1964. Biological Conrol of Insect Pests and Weeds. New York: Reinhold.

Dennill, G.B. and Moran, V.C., 1989. On insect-plant associations in agriculture and the selection of agents for weed biocontrol. Annals of Applied Biology 114 : 157-166.

Dennill, G.B., and Hokkanen, H.M.T., 1990. Homeostasis and success in biological control of weeds. Agriculture, Ecosystems and the Environment 33 : 1-10.

Drooz, A.T., Bustillo, A.E., Fedde, F.G. and Fedde, V.H., 1977. North American egg parasite successfully controls a different host genus in South America. Science ,197 : 390-391.

Ehler, L.E., 1987. Ecology of Rhopalomyia californica Felt at Jasper Ridge (Diptera: Cecidomyiidae). Pan-Pacific Entomology, 63 : 237-241.

Floyd, R.B. and Easteal, S. , 1986. The giant toad (Bufo marinus): introduction and spread in Australia. p. 151 In:Graves, R.H. .and Burdon, J.J. (eds). Ecology of biological invasions . Cambridge Univ. Press: Cambridge.

Goldson, S.L., Proffitt, J.R. and McNeill, M.R., 1990. Seasonal biology and ecology in New Zealand of Microctonus aethiopoides (Hymenoptera: Braconidae), a parasitoid of Sitona spp. (Coleoptera: Curculionidae), with special emphasis on atypical behaviour. Journal of Applied Ecology, 27: 703-722.

Gould, F., 1988. Evolutionary biology and genetically engineered crops. Bioscience , 38: 26-33.

Harris, P., 1990. Environmental impact of introduced biological control agents. pp. 289-299. In: Mackauer, M. , Ehler,L. and Roland, J. (eds). Critical issues in biological control. Intercept: Andover, Hants.

Hokkanen, H.M.T. and Pimentel, D., 1984. New approach for selecting biological control agents. Canadian Entomologist, 116: 1109-1121.

Hokkanen, H.M.T., and Pimentel, D. , 1989. New associations in biological control: theory and practice. Canadian Entomologist, 121 : 828-840.

Howarth, F.G., 1991. Environmental impacts of classical biological control. Annual Review of Entomology, 36: 485-509.

Huffaker, C.B., 1980. New Technology of Pest Control. Wiley: New York.

Huffaker, C.B.,Simmonds, J.F. and Laing, J.E., 1976. The theoretical and empirical basis of biological control. pp. 41-78. In: Huffaker, C. B. and Messenger, P. S. (eds). Theory and Practice of Biological Control. Academic Press: New York.

Huffaker, C.B., Messenger, P.S. and DeBach, P., 1971. The natural enemy component in natural control and the theory of biological control. pp. 16-67. In: Huffaker,C. B. Biological Control. Plenum: New York.

Lawton, J.H., 1988. Biological control of bracken in Britain: constraints and opportunities. Philosophical Transactions of the Royal Society London Series B, 318 : 335-354.

Legner, E.F., 1986. Importation of exotic natural enemies. pp. 19-30. In: Franz,J. M. (ed) .Biological Plant Health Protection. Gustav Fischer Verlag: Stuttgart.

Lewis, W.J. and Martin, W.R., 1990. Semiochemicals for use with parasitoids - status and future. Journal of Chemical Ecology, 16: 3067-3089.

Miller, M.C., Moser, J.C. McGregor, M. Gregoire, J.C. Baisier, M. Dahlsten, D.L. andWerner, R.A., 1987. Potential for biological control of native American Dendroctonus beetles (Coleoptera: Scolytidae). Annals of the Entomological Society of America, 80 : 417-428.

Moser, J.C., and Branham,S.J., 1988. Bugs that eat bugs. Forest Farmer, 47 : 17-20.

Oka, I.N., and Pimentel, D., 1976. Herbicide (2,4-D) increases insect and pathogen pests on corn. Science, 193 : 239-240.

Oka, I.N., Pimentel, D., Iqbal, A. and Suryawan, I.B.G., 1991. Ecology and Population Dynamics of Aphids and other Arthropods Associated with Soybean and Mungbean Crops. Special Edition #3. Bogor, Indonesia. Agency for Agricultural Research and Development: Bogor Research Institute for Food Crops.

Pacala, S.W., Hassell, M.P. and May, R.M., 1990. Host-parasitoid associations in a patchy environment. Nature, 344: 150-153.

Pimentel, D. 1963. Introducing parasites and predators to control native pests. Canadian Entomologist, 95 : 785-792.

Pimentel, D. 1986. Population dynamics and the importance of evolution in successful biological control. pp. 3-18. In: Franz,J. M. (ed) .Biological Plant Health Protection. Gustav Fischer Verlag: Stuttgart.

Pimentel, D., Acquay, H., Biltonen, M., Rice, P. , Silva, M., Nelson, J., Lipner,V., Giordano, S., Horowitz, A. and D'Amore,M., 1992a. Assessment of Environmental and economic costs of pesticide use. in press. In: Pimentel, D. and Lehman,H. (eds). The Pesticide Question: Environment, Economics and Ethics. Chapman and Hall: New York.

Pimentel, D., Glenister, C., Fast, S. and Gallahan,D., 1984. Environmental risks of biological pest controls. Oikos, 42 : 283-290.

Pimentel, D., Hunter, M.S., LaGro, J.A., Efroymson, R.A., Landers, J.C., Mervis, F.T., McCarthy, C.A., and Boyd, A.E. ,1989. Benefits and risks of genetic engineering in agriculture. Bioscience , 39: 606-614.

Pimentel, D., Stachow, U., Takacs, D.A., Brubaker, H.W., Dumas, A.R., Meaney, J.J., O'Neil, J., Onsi, D.E. and Corzilius,D.B., 1992b. Conserving biological diversity in agricultural/forestry systems. BioScience, in press

PSAC., 1965. Restoring the Quality of Our Environment. . Washington, DC: Report of the Environmental Pollution Panel. President's Science Advisory Committee. The White House. November.

Reddy, M.S., 1991. Biological control of plant diseases. pp. 33-41. In: McClay, A.S. Proceedings of the Workshop on Biological Control of Pests in Canada, October 11-12 1990. Calgary, Alberta. . Alberta Environmental Centre, Vegreville, Alberta.

Roitberg, B.D., 1990. Variation in behaviour of individual parasitic insects: bane or boon? pp. 25-39. In: Mackauer, M., Ehler, L., and Roland,J., Critical issues in biological control. Intercept: Andover, Hants.

Roush, R.T. 1990. Genetic variation in natural enemies: critical issues for colonization in biological control. pp. 263-287. In: Mackauer, M., Ehler, L., and Roland,J., Critical issues in biological control. Intercept: Andover, Hants. Intercept.

Sweetman, H.L., 1958. The Principles of Biological Control. W.C. Brown: Dubuque, Iowa:

Thomas, M.B., Wraiten, S.D. and Sotherton,N. W., 1992. Creation of island habitats in farmland to manipulate populations of benefical arthropods: predator densities and emigration. Journal of Applied Ecology. In press.

Thompson, D.Q., Stuckey, R.L. and Thompson,E.B., 1987. Spread, impact and control of purple loosestrife (Lythrum salicaria) in North American wetlands. Fish and Wildlife 2, US Dept. Interior, Washington, D.C.

Tisdell, C.A., 1990. Economic impact of biological control of weeds and insects. pp. 301-315. In: Mackauer, M., Ehler, L., and Roland,J., Critical issues in biological control. Intercept: Andover, Hants. Intercept.

Turnock, W.J., 1991. Biological control of insect pests of field crops. In Proceedings of the Workshop on Biological Control of Pests in Canada, October

11-12 1990. Calgary, Alberta. McClay, A.S. 9-14. Alberta Environmental Centre, Vegreville, Alberta.

Turnock, W.J., Taylor, K.L., Schroeder, D. and Dahlsten, D.L., 1976. Biological control of pests of coniferous forests. pp. 289-311. In: Huffaker,C. B. and Messenger, P.S. Theorgy and Practice of Biological control. Acadmic Press: New York.

van Emden, H.F. 1990. Plant diversity and natural enemy efficiency in agroecosystems. pp. 63-79. In: Mackauer, M., Ehler, L., and Roland,J., Critical issues in biological control. Intercept: Andover, Hants. Intercept.

Waage, J.K., 1990. Ecological theory and the selection of biological control agents. pp. 135-157. In: Mackauer, M., Ehler, L., and Roland,J., Critical issues in biological control. Intercept: Andover, Hants. Intercept.

Waage, J.K., 1992. Biological control in the year 2000. In press. In: Barlow,H. (ed). Pest management and the environment in the year 2000. CAB International.

Wapshere, A.J., Delfosse. E.S., and Cullen, J.M., 1989. Recent developments in biological control of weeds. Crop protection, 8: 227-250.

Zwolfer, H., Shani, M.A. and Rao,V.P., 1976. Foreign exploration and importation of natural enemies. pp. 198-207. In: Huffaker,C. B. and Messenger,P. S. (eds). Theory and Practice of Biological Control. Academic Press: New York.