Opportunities for Biological Control of Agricultural Pests in Developing Countries

D.J. Greathead and J.K. Waage
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The World Bank
Washington, D.C., U.S.A.
# Table Of Contents

| SUMMARY | iii |
| ACKNOWLEDGEMENTS | v |

## CHAPTER I  BACKGROUND AND ACHIEVEMENTS OF BIOLOGICAL CONTROL

- The Kinds of Biological Agents  2
- How Biological Control Agents Are Used  4
- Successful Biological Control to Date  5
- Conclusions  8

## CHAPTER II  IMPLEMENTATION OF BIOLOGICAL CONTROL

- Introduction  10
- Augmentation, Inoculation and Inundation  14
- Conclusions  15

## CHAPTER III  BROAD ASSESSMENT OF BIOLOGICAL CONTROL POTENTIAL

- Pest Ecology  16
- Pest Damage  18
- Cropping Systems  18
- Control of Weeds  19
- Conclusions  19

## CHAPTER IV  BIOLOGICAL CONTROL IN MAJOR CROPS

- CEREALS  20
  - Wheat and Barley  21
  - Rice  21
  - Tropical Dryland Cereals  22

- ROOT CROPS  23
  - Sweet Potatoes  23
  - Cassava  23

- GRAIN LEGUMES  24

- OIL SEEDS  24
  - Groundnut  24
  - Castor  24
  - Sesame, Safflower, Sunflower  25

- PLANTATION CROPS  25
  - Sugarcane  25
  - Coffee  26
  - Tea  27
  - Cocoa  27
  - Coconut  27
  - Oil Palm  28
<table>
<thead>
<tr>
<th>Category</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber</td>
<td>29</td>
</tr>
<tr>
<td>Tobacco</td>
<td>29</td>
</tr>
<tr>
<td>FIBRES</td>
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<tr>
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<td>29</td>
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<tr>
<td>VEGETABLES</td>
<td>30</td>
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<tr>
<td>POTATO</td>
<td>30</td>
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<tr>
<td>Cabbage and other Brassica Crops</td>
<td>31</td>
</tr>
<tr>
<td>FRUITS</td>
<td>31</td>
</tr>
<tr>
<td>Banana</td>
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</tr>
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</tr>
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<td>32</td>
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<tr>
<td>Pastures</td>
<td>32</td>
</tr>
<tr>
<td>MAJOR PEST PROBLEMS AFFECTING SEVERAL CROPS</td>
<td>33</td>
</tr>
<tr>
<td>Migratory Pests</td>
<td>33</td>
</tr>
<tr>
<td>Pantropical Pests</td>
<td>34</td>
</tr>
<tr>
<td>WEEDS</td>
<td>36</td>
</tr>
<tr>
<td>Conclusions</td>
<td>39</td>
</tr>
</tbody>
</table>

FURTHER READING

APPENDIX A. CHOICE OF CROP AND ASSESSMENT OF THE PROBABILITY FOR SUCCESS OF DIFFERENT APPROACHES TO PEST CONTROL 41
SUMMARY

Biological control is the use of living organisms as pest control agents. It may operate alone or as a component of integrated pest management.

The most widely used and successful method, the introduction and establishment of appropriate organisms, aims at providing permanent control of a particular pest. Biological control by inoculation, augmentation or inundation is also practised, but this requires continuous or periodic mass-rearing of control agents for release. Beneficial organisms already present in the crop may also be conserved to enhance their impact on the pest with temporary or permanent results. Introduction, which produces long-term results, is preferred as no further input is required, biological or chemical, once control has been established. With the other methods, regular farmer cooperation is necessary.

The most frequently used biological control agents are insects, which are released to control both insect pests of crops and weeds. The desirable qualities of these agents include their great diversity, high degree of specificity and ease of handling. Pathogens for the control of insects and weeds have great potential, but our knowledge of their use has only recently reached the stage where practical programmes can be implemented. New production techniques are leading to their development as biological pesticides which is likely to be their principal future role in pest control.

The prospects for control of vertebrate pests are poor. On the other hand, prospects are good for the development of biological control of plant diseases, but research is still at an early stage. Recent research on soil-inhabiting nematode worms shows promise that biological control programmes for these pests will eventually be developed.

Because biological control may provide long-term or even permanent results, causes no pollution, and poses no risk to human health, it should always be a preferred control measure when economically competitive with other methods. In developing countries, it will have special application where the cost of chemical control is prohibitively expensive (e.g. subsistence farming) and where the inappropriate or excessive use of chemicals has resulted in high levels of pest resistance.

This report emphasizes the method of introduction because of its many successes to date (Tables II & III) and the great economies it may offer relative to the other methods, particularly chemical control (Table II). The cost of implementing a programme of introduction is discussed and evaluated in terms of the convenient currency of scientist years.

The degree of success of a particular introduction programme, however, cannot be precisely predicted, owing to the many complex ecological factors involved in the interaction between populations of pest and control agent. By application of ecological theory, tempered by
experience, one can however make general predictions as to when introduction and other biological control methods are likely to succeed. Introduction will be most effective against pests which (a) have a moderate-to-low reproductive rate, (b) tend to form local, non-migratory populations and (c) do not do direct damage to the harvested portion of the crop. Introduction will be most successful in crops which persist locally for long periods with little regular cultivation, and least successful in rapidly growing, annual field crops. Where introduction is not favored, inoculation, augmentation or inundation may be appropriate.

The prospects for biological control in specific crops with a substantial production in developing countries are reviewed in detail, against the background of the foregoing predictive analysis. As there are few immediate prospects for the biological control of plant diseases, nematodes and annual weeds, the review concentrates on the potential for control of insect pests and perennial weeds. Pests of major importance affecting several crops are given special treatment. When available, estimates of the cost of initiating action against particular pests are given. Broadly, the best prospects are to be found in plantation crops and pasture land, and to some extent in annual crops when they are grown on a large scale throughout the year. Urgent coordinated action is required to evaluate the potential for biological control in the integrated management of whitefly, Heliothis, and moth stem borers of cereals and sugarcane in the Old World.
Acknowledgements

The authors are particularly grateful to the following for comments, criticism and guidance in the preparation of this paper:

Dr. F.D. Bennett, Director, CIBC;

Dr. J. Bridge, ODA Nematologist, Rothamsted Experiment Station;

Dr. H.C. Evans, ODA Forest Mycologist, Commonwealth Mycological Institute;

Mr. D.J. Girling, CIBC;

Dr. P. Harris, Canada Agriculture;

Dr. D.J. Hunt, Commonwealth Institute of Parasitology;

Drs. J.D. Mumford and G.A. Norton Imperial College;

Dr. J. Waller, ODA Liaison Officer, Commonwealth Mycological Institute;

Professor M.J. Way, Consultant Director, CIBC, Imperial College

We are also grateful to the many colleagues who have made helpful suggestions and clarified a number of points.
Chapter I

BACKGROUND AND ACHIEVEMENTS OF BIOLOGICAL CONTROL

In this report, biological control is understood to imply the use of living organisms as pest control agents. These include vertebrates, invertebrates and a wide variety of microbial pathogens, including fungi, bacteria and viruses. Many of these disease-producing agents are made up in formulations and applied in the same way as chemical pesticides, and with similar short-term results. Use of control agents as biological pesticides will be largely outside the scope of this report, as will be the application of certain specific methods of control which are sometimes imprecisely labelled 'biological control' (e.g. the use of behavior-modifying chemicals, autocidal genetic methods, sterile male releases, the breeding of crop varieties resistant to pests and some forms of environmental modification).

Until powerful synthetic pesticides became freely available after World War II, pest control necessarily depended on the application of all available methods; cultural, mechanical, chemical and biological. Over the last 30 years, the dominance of chemical control stifled the development and application of other approaches particularly biological. However, the alarming rise in resistance to chemical pesticides, together with growing concern for their environmental impact, has led to renewed interest in biological control as often an inexpensive and safe component of integrated pest management (IPM). 1/

IPM involves the suppression of pests, or avoidance of pest attack, by employing all appropriate pest control methods, including agronomic procedures and manipulation of the crop environment. In practice, its aim is very often merely the modification of existing pest control strategies so as to minimize input of chemical pesticides.

The President of the USA in his 1979 Environmental Message provided a succinct definition which indicates the objectives:--

"IPM uses a systems approach to reduce pest damage to tolerable levels through a variety of techniques, including natural predators and parasites, genetically resistant hosts, environmental modification and, when necessary and appropriate, chemical pesticides. IPM strategies generally rely upon biological defenses against pests before chemically altering the environment."

1/ Integrated Pest Control (IPC) is treated as a synonym of IPM in accord with the conclusion of FAO.
Biological control should thus be one of the first components considered in IPM. Historically, it has usually been considered last, if at all. Its relative importance in IPM will vary from pest to pest and crop to crop; sometimes its contribution will be limited, whatever effort is put into development. In other pest or crop systems it may prove the major, if not the sole method necessary for effective management. When biological control works in this manner, the economic returns relative to chemical methods can be enormous. Predicting where biological control will succeed and when it will be most cost effective, is a particularly difficult task, owing to the great diversity in control agents, the ways in which they can be used and the factors which influence success.

Towards this end, we begin in this Chapter with a Section describing the different kinds of biological control agents followed by a description of different strategies for their use and the results attained to date. In Chapter 2, we will describe the best conditions and procedures for implementation and the economics of biological control. In Chapter 3 we will identify the kind of pests against which biological control is most likely to succeed, and thereby derive some general priorities for its use. Finally, in Chapter 4 we will develop specific priorities for biological control programmes on the most important tropical crop systems and against pests of special importance.

The Kinds of Biological Control Agents

Biological control has a long history and could be said to date from the domestication of cats and their employment to protect stored food from the ravages of mice and rats. The notion of introducing exotic species to suppress pests developed in island communities and the first successful introduction for this purpose is claimed to be that of the Indian Mynah into Mauritius in 1762 for control of the Red Locust. Later introductions of vertebrate predators, chiefly mongooses, on to islands in the Caribbean and Indian Oceans for rat control were less successful as the predators themselves became pests, killing chickens and native birds as well as rats. As a result, such general predators are no longer introduced as pest control agents. Modern biological control depends rather upon the use of specific natural enemies of the target pest carefully selected and screened to eliminate species which could pose a threat to other useful organisms.

It was not until the 19th century that the possibility of employing beneficial insects and microbes was appreciated and various proposals made, but spectacular results were not obtained until 1888. In that year, an Australian ladybird was imported into California for control of the cottony cushion scale, a pest which threatened to destroy the California citrus industry. The resulting complete suppression of this pest was widely publicized and soon repeated elsewhere.

1/ Details of examples mentioned in the test will be found in the reviews listed under "Further reading."
From this propitious start, insect natural enemies have gradually become the major agents used in the biological control of crop pests. They are conveniently classified as either predators or parasitoids, which differ somewhat in their attributes:

(a) **Predators.** The important characteristics of predators are that individuals consume a number of prey during their lifetime and that they are active organisms which seek their food. There is a range from species consuming a wide range of prey species (polyphagous) to extreme specialists (monophagous). Polyphagous arthropod predators, like the vertebrate predators mentioned above, are usually of little use in biological control as they do not concentrate their attention on the target pests, tending to feed on the most abundant and easily captured prey. They may also include useful species in their diet. Monophagous predators or species with a narrow range of prey (oligophagous) are more likely to have desirable characteristics. Ladybird beetles, many species of predatory bugs, lacewings and the larvae of hover flies are common insect predators.

(b) **Parasitoids.** These insects develop parasitically in a single host which is eventually killed. Thus individual parasitoids only consume one prey (or host) during their lifetime. This unique lifestyle is exhibited by a remarkably diverse group of small wasps and flies, comprising about 300,000 species, or about 1/10 of all species of multicellular organisms. Although the larval stage is parasitic, the adults are free-living and highly mobile so that they are able to search actively for hosts in which to lay eggs, and may themselves feed as predators, many are entirely monophagous.

(c) **Insects for weed control.** Plant-feeding insects are widely used for biological control of weeds. These insects belong to the same taxonomic groups as insects which are pests of crop plants, and have similar life-histories, but the high levels of host plant specificity which they exhibit ensure that they will attack only the target weed species. Thus, they may be used safely beside, or even within agroecosystems, without risk to crops.

Although insects have received the greatest attention as biological control agents, other organisms have been investigated and used, particularly nematode worms, microorganisms (protozoa, bacteria, rickettsia and viruses) and fungi. These disease-causing agents share many biological properties, but a useful distinction can be made between larger parasites such as nematodes, and the smaller pathogens, such as microorganisms and fungi.

(d) **Parasites.** Parasitic organisms tend to weaken rather than kill their hosts. They depend on the host throughout their existence.
except for short periods when they disperse. This stage is usually a passive egg or spore which requires an efficient dispersal agent if the parasite is to be useful in long-term control. Except for a few instances, e.g. nematode parasites of insects, parasites have not so far found a place as useful control agents.

(e) **Pathogens.** Parasitic microorganisms will often kill their host outright. Dead hosts liberate millions of individual microbes which are dispersed by the wind and rain. Because of their minute size and rapid reproduction in the host, pathogens are easier to mass-produce than parasites and can be released against pests using equipment developed for the application of chemical pesticides.

(f) **Antagonists.** There are biological control agents which influence the abundance of pests but do not feed directly on them. They are thought to decrease pest populations by competitive exclusion which may involve either simple physical exclusion or the secretion by the antagonist of substances (e.g. antibiotics) which inhibit the pest. This type of agent is of particular importance in biological control of plant pathogens and the term antagonist is preferred by plant pathologists to describe control agents especially when their mode of action is incompletely understood.

How Biological Control Agents Are Used

The diverse agents described above can be used in a variety of ways for the control of agricultural pests. The biological properties of a particular type of control agent will largely determine which of the following strategies will be most appropriate:

(a) **Introduction.** This is now commonly referred to as "classical biological control." An exotic beneficial organism is introduced into a new area and becomes permanently established. When successful, pest mortality is increased to the extent that the pest becomes of negligible importance, a biological balance is achieved and control continues indefinitely. This method has been used most frequently against introduced pests which are presumed to have arrived in a new area without their natural controlling factors; they are then sought in the area of origin of the pest. However, it can also be used against native pests that lack effective natural enemies or where natural biological control has been upset by intensified agriculture.

(b) **Augmentation.** Where the numbers of native natural enemies are inadequate, because their numbers do not build up sufficiently rapidly, or because they are unable to maintain adequate densities under present agricultural practice, their numbers may be usefully increase by releases of laboratory-bred individuals.
(c) **Inoculation.** Where a native natural enemy is absent from a particular area, or an introduced species is unable to survive permanently, inoculative releases can be made at the beginning of a season or as a new crop develops to colonize the area for the duration of the season or crop, and so prevent pest build-up.

(d) **Inundation.** Very large numbers of a native or introduced natural enemy, very often a pathogen, are cultured and applied at critical periods for short-term suppression of pest numbers, in much the same way as most chemical pesticides.

(e) **Conservation.** This is an indirect method in that measures are taken to conserve natural enemies and enhance the numbers of species already present in the crop environment.

Short of total eradication, which is seldom feasible, successful biological control by introduction is the most nearly perfect means of pest control and, for this reason, "classical biological control" has so far been the aim of most practitioners. All methods are unlikely to cause environmental pollution. Also, the development of pest resistance to biotic control agents is usually negligible and so does not require recurrent input of effort or money once it has been established. The main disadvantage is the near impossibility of predicting in advance the precise level of control which will be attained because of the complexities of the interactions of animals, plants, climate and soils which are so great that fully predictive models are not yet feasible.

**Successful Biological Control To Date**

The preceding sections have demonstrated the great range of biological control agents and methods for their application. The pattern of success which we will now discuss necessarily reflects both the relative merits of different agents and methods, and historical factors which have focussed attention unevenly across the spectrum of biological control.

(a) **Vertebrates.** The biological control of vertebrate pests has shown little promise. Their predators are usually too polyphagous, and their pathogens pose too great a medical risk (with the notable exception of the specific Myxoma virus used for rabbit control in Europe and Australia) to be considered at present for the control of such important pests as rats, mice and birds.

(b) **Insects.** By contrast, the biological control of insect pests has proven highly successful. This has been achieved largely through the use of insect predators and parasitoids, with introduction the major strategy. Over 750 species of insect natural enemies have been introduced for the control of more than 250 species of invertebrate agricultural pest, mostly insects, but also snails and mites.\(^1\) According to Huffaker & Messenger (1976), there

\(^1\) See Clausen (1978)
were 327 successful instances of biological control of which 102 provided complete suppression by 1975.

In more than 100 of the cases of successful introduction, the insect agent(s) introduced have given complete control of the pest, thus obviating the need for any other component of IPM. Where complete success has not been achieved, successful introductions have greatly increased the biological control component of IPM, and thereby reduced the cost of other components, particularly pesticide application.

In addition to introduction, the release of laboratory-reared insect natural enemies for augmentation, inoculation and inundation has given effective control for certain pests. Spectacular success has been obtained in the control of insect and mite pests in glasshouses by regular releases of parasitoids and predators. The success of these methods in field crops has been more difficult to evaluate, but many programmes for field mass-release exist, particularly in China and the Soviet Union.1/ Perhaps the most widely-used agent is the parasitoid of insect eggs, Trichogramma, which is released inundatively for the control of temperate and tropical moth pests on an estimated 17,000,000 ha of cropland worldwide.

Insect pests may also be controlled by parasites and pathogens. To date, the use of nematode parasites of insects has shown promise for the control of mosquitoes and a few agricultural pests, but commercial development has been slow. One bacterial pathogen, Bacillus thuringiensis, is available commercially and widely used. It is a relatively broad spectrum agent used against larvae of moth and butterfly pests. Viral pathogens show considerable promise. Over 300 viruses of insect pests are known, but only three are yet available commercially. Viruses have a greater specificity than bacteria, which is desirable in some ways, but limits markets for commercial development. While fungi are the most diverse of all insect pathogens, their development as control agents has been slow; four species are now commercially available for use in field crops, one of which, Metarhizium anisopliae, gives effective control of spittlebugs on sugarcane and forage in Brazil, and rhinoceros beetle on coconut palms in Western Samoa. Protozoan control agents for insects are also at an early stage of development.

Intensive research is currently focused on the development of parasites and pathogens for insect control, and rapid advances in development and registration of such agents for commercial use are to be expected. Some parasites and many pathogens can be mass-produced by fermentation and are utilized in the same manner as chemical pesticides. However, introduction of exotic disease agents deserves more

1/ See Ridgeway & Vinson (1977)
attention. Ecological studies predict that the best disease agents for long-term pest control will exhibit moderate pathogenicity in contrast to the highly pathogenic forms being developed for inundative use.²/

(c) Nematodes. Plant feeding nematodes have few natural enemies. Although fungi which trap nematodes moving through the soil are marketed in France for use in mushroom beds and tomatoes grown under glass, under field conditions results have been poor. Of greater interest are fungi parasitic on root cyst nematodes which are effective in cereal fields when favorable cultural practices are employed, but much more research is required before their value for nematode control can be assessed.

(d) Plant diseases. Biological control of plant diseases has progressed further. There are now six commercially viable systems available for control of specific diseases of temperate crops (see Table I). The possibilities for major diseases of tropical crops are only now beginning to be seriously investigated and one useful fungal antagonist has recently shown promise in preliminary field tests against cocoa witches' broom and cocoa canker in Brazil.

<table>
<thead>
<tr>
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<tr>
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<td>peach, etc.</td>
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<tr>
<td>Stem rot</td>
<td>carnation</td>
<td>U S A</td>
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<tr>
<td>Brown blotch</td>
<td>mushroom</td>
<td>Australia</td>
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<td>Fungal pathogens</td>
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<tr>
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<td>plum etc.</td>
<td>U K</td>
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<td>Root rot</td>
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<td>U K</td>
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<tr>
<td>Dry bubble</td>
<td>mushroom</td>
<td>Sweden</td>
</tr>
</tbody>
</table>

(e) Weeds. The introduction of plant feeding insects to control weeds has met with considerable success. (See Table II and for savings relative to chemical control see Table III - Klamath weed and Skeleton weed).

²/ See Andersen (1982)
The introduction of pathogens for the control of exotic weeds shows considerable promise. Already, rust fungi have been successfully used against Skeleton weed in Australia and Blackberries in Chile.

Table II

<table>
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<tr>
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<tr>
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Conclusions

Across the spectrum of agricultural pests, biological control has been applied more often and consequently been more successful, in the control of insect pests and weeds. The present assessment will therefore concentrate on these categories of pests, where implementation of biological control in developing countries can be most rapid. The prospects for control of vertebrates are negligible and those for nematodes and plant diseases are hopeful, but a great deal more fundamental research is needed before their potential can be fully evaluated.

1/ From Julien (1982)
Chapter II

IMPLEMENTATION OF BIOLOGICAL CONTROL

Biological control may find useful application in developing countries in several agricultural contexts.

(a) Where the value of a crop is too low and extension advice inadequate to permit the use of pesticides or other expensive control methods. Here, the strategy of introduction which, if successful, involves no recurrent costs, may be particularly appropriate; for example, other control measures against rangeland weeds are often prohibitively expensive. In small-scale farming and subsistence agriculture, farmers may not be able to afford the pesticides used by large scale commercial growers. Then biological control may provide essential control for small farmers and less expensive control for the large farmers who may contribute to the cost of implementation. Thus, biological control undertaken primarily to control a devastating mealybug pest on coffee estates in Kenya also benefitted small farmers in controlling this mealybug on yams and vegetable crops.

(b) Where overuse of insecticides has created pesticide resistance so high that other control methods become necessary. In this context, conservation, coupled with a reduction in pesticide use, may result in effective natural control, which may be further enhanced by augmentation and introduction. The collapse of the cotton industry in the Canete Valley of Peru due to overuse of insecticides is a case in point. Resistance to insecticides increased so rapidly over a five-year period that in the final year of collapse, applications were being made every three days with little success. Following reduction of pesticide use, predators and parasitoids had to be reintroduced from surrounding regions and conserved.\(^1\) A similar agricultural crisis currently exists in brassica farming in Southeast Asia, where the Diamond back moth (Plutella xylostella) now exhibits resistance to all known insecticide groups.\(^2\)

(c) Elsewhere in cropping systems where biological methods are not currently part of an already adequate pest management programme, biological control may be usefully introduced if it is economical and compatible with existing methods. The difficulty in the use of a specific biological control agent to control only one of a

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1/ See DeBach (1974)

complex of pests on a crop, when chemical control must be continued for other pests, is that the chemicals may reduce the effect of the agent on the target pest. Thus, the best systems for biological control are those with one, or at most a few, major pests. However, biological and chemical control methods are not always incompatible. Selective insecticides and microbial agents can be used effectively with parasitoids and predators in IPM systems and even the regular use of pesticides with high toxicity does not preclude the use of natural enemies in pest management, e.g. when chemicals can be applied so as to avoid undue natural enemy mortality or when pesticide resistant strains of natural enemies are available.

Other factors which should be considered when the feasibility of biological control is evaluated include the importance to the user of eliminating medical risks, environmental pollution and the long-term threat of pesticide resistance generated by the use of chemical control measures.

We will now consider the development and implementation of biological control programmes in tropical countries, both from a methodological and economic perspective. Effective biological control requires a thorough understanding of the population biology of the pest, an understanding rarely attained in chemical control programmes. A study must therefore first be made of the mortality factors acting on the different life stages of the pest, their relative severity and the natural enemies which contribute to them. This will help to pinpoint the most vulnerable stages in the pest's life and the kinds of agents affecting that stage. With this knowledge, conservation measures for existing natural enemies may be developed (which may involve changing the timing or number of pesticide applications, modifying cropping practices or providing food and shelter for natural enemies), and a programme of introduction or regular release (augmentation, inoculation, inundation) of the appropriate natural enemies can be undertaken. We will consider these two methods in turn.

Introduction

When natural enemies are required from outside the target area, the assistance of a national or international agency is required to undertake foreign exploration. This usually comprises the following steps:

(a) Formulation of a project. This requires an assessment of existing knowledge of the pest in the target area and a literature survey to determine the origin of the pest and what is already known of its natural enemies. An area for exploration is then selected, preferably in the area of origin of the pest or where the climate and environmental conditions are as similar to the target area as possible. A plan of action with estimates is then submitted.

(b) Exploratory work overseas. On approval of the project, surveys are made to obtain an inventory of natural enemies, pest
incidence and seasonality so as to select sites where the life history, incidence and host range of the natural enemies are studied.

(c) **Selection and screening of control agents.** A preliminary report is submitted from which promising natural enemies are selected for in-depth study in the field and in the laboratory to provide information on their host specificity, safety and culture methods. Detailed reports are then submitted to the importing country for approval of importation.

(d) **Importation.** Species cleared for importation are screened to eliminate disease and other unwanted contaminants and shipped to the receiving country. There, further tests may be carried out in quarantine before cultures are distributed.

(e) **Assessment.** Following the first releases, progress should be monitored for as long as possible to obtain an assessment of the effects of the introduction on the pest and to allow adjustment of technique to achieve the maximum benefit.

The process outlined takes at least 2-3 years per control agent, but where an effective agent is known and used elsewhere, importation can proceed as soon as a culture is located and clearance is obtained. When success is not achieved with the first importations or difficulties are encountered in locating, handling, culturing or establishment of natural enemies, the process may take longer. The limit is determined by consideration of the likelihood of success, availability of alternative control measures and of funding. Ideally, the project should not be abandoned until all promising leads have been explored.

Not all introductions will lead to establishment of control agents and successful pest suppression. An assessment of the data in Clausen (1978) indicates that about 30% of parasitoids and predators introduced against insect pests became established. Furthermore, not all of these established agents contribute significantly to pest control. There is, however, evidence that the level of success in an introduction programme is proportional to the amount of effort; many failures at establishment may be merely the consequence of inappropriate methods or control agents. These constraints on success are discussed in Chapter III and Appendix A. Even when circumstances are favourable, biological control may not be possible because suitable agents are not available at present (e.g. for rats, banana weevil and sisal weevils). In these instances, persistence with research may be rewarded by finding ways of overcoming the difficulties or alternative agents may be discovered. More serious are avoidable technical and administrative failures. Technical failure may be due to inadequate training of personnel, insufficient dedication to the task in hand, or inadequate facilities. Administrative failure stems from inadequate financial support and from lack of understanding by officials.
which can obstruct the speedy despatch and effective use of biological control agents.\textsuperscript{1/}

Multiple introduction of control agents is generally the rule. Fears that multiple introductions lead to competition between agents and reduce control have been dispelled by subsequent ecological analyses which have shown that, providing due care is taken in choosing the agents to be used, any additional mortality caused by adding further biological control agents to the system will add to the overall level of control.

Proper economic assessment of introduction programmes has been limited, with somewhat more information available on the cost of introduction than on the benefits. Dr. Peter Harris\textsuperscript{2/} has calculated that the successful control of a pasture weed has required on average the introduction and release of 4–5 control agents at a cost of 4–5 scientist years per agent. However, in many instances of successful insect pest control, only 2–3 agents have had to be released.

Scientist years are convenient units for calculating costs of classical biological control, which largely involves research, as they can be transformed into the yearly cost of employing and equipping a scientist in a particular year and country - in the Canadian case, the total cost was between US$1.2 and US$1.5 million. Considerable savings can be made if previous biological control work has been done on the pest, such that the species and source of predators and parasitoids are known.

When control is obtained from an introduction, the benefits are usually equated with the annual costs of losses and of alternative control methods necessary in the absence of introduced agents, which may be discounted and summed over a number of years. Such benefits are often enormous, as shown in Table III, which summarises most of the economic information available for biological control projects. Only recently have economists taken an interest in the evaluation of biological control programmes and it is hoped that this new interest and better evaluation of future projects will put the economics of biological control on a more firm footing.


### Table III

**SOME ESTIMATES OF BENEFITS ACCRUING FROM BIOLOGICAL CONTROL**

**A.** California 1923-59 from DeBach (1964)

<table>
<thead>
<tr>
<th>Pest (date controlled)</th>
<th>Total savings over previous losses plus pest control costs US$ millions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Citophilus mealybug (1930)</td>
<td>56.0</td>
</tr>
<tr>
<td>Black scale (1940)</td>
<td>32.0</td>
</tr>
<tr>
<td>Klamath weed (1953)</td>
<td>20.9</td>
</tr>
<tr>
<td>Grape leaf skeletoniser (1949)</td>
<td>0.75</td>
</tr>
<tr>
<td>Spotted alfalfa aphid (1958)</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Total savings on 5 projects 115.3
Total spent over period 4.3

**B.** Australia projected to 2000 AD at 1975 values discounted at 10%.1/

<table>
<thead>
<tr>
<th>Pest</th>
<th>Cost of research by CSIRO (Equiv)</th>
<th>Total Benefits (Equiv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skeleton weed</td>
<td>2.39 A.$-million-US$</td>
<td>264.4A.$-million-US$</td>
</tr>
<tr>
<td>Wood Wasp</td>
<td>6.27 A.$-million-US$</td>
<td>15.4A.$-million-US$</td>
</tr>
<tr>
<td>White Wax scale</td>
<td>1.07 A.$-million-US$</td>
<td>1.7A.$-million-US$</td>
</tr>
<tr>
<td>Two-spotted mite</td>
<td>0.67 A.$-million-US$</td>
<td>17.5A.$-million-US$</td>
</tr>
<tr>
<td>Red Scale</td>
<td>not available</td>
<td>17.7A.$-million-US$</td>
</tr>
</tbody>
</table>

**C.** Benefits of some tropical CIBC projects as supplied by sponsors 2/

<table>
<thead>
<tr>
<th>Pest</th>
<th>Country</th>
<th>Total Cost 2/ US $</th>
<th>Benefit (year assessed) US$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rufous scale</td>
<td>Peru</td>
<td>1,789.14</td>
<td>$226,916 p.a. saved on chemical control (1977)</td>
</tr>
<tr>
<td>Barnacle scale</td>
<td>Hawaii</td>
<td>-</td>
<td>$110,000 p.a. increased yield (1974)</td>
</tr>
<tr>
<td>Sugarcane scale</td>
<td>Tanzania</td>
<td>11,975.88</td>
<td>$67,832.16 p.a. increased yield (1974)</td>
</tr>
<tr>
<td>Sugarcane borer</td>
<td>Brazil</td>
<td>9.54/ha p.a.</td>
<td>$48.15/ha p.a. (1979)</td>
</tr>
<tr>
<td>Coconut leafminer</td>
<td>Sri Lanka</td>
<td>35,782.95</td>
<td>$12.4 million p.a. in crop saved (1977)</td>
</tr>
</tbody>
</table>


Augmentation, Inoculation and Inundation

This form of biological control requires mass-culture of control agents and a recurrent cost. It therefore must be competitive in economic terms with other methods, particularly chemical control.

With prolonged mass culture of predators, parasitoids, parasites or pathogens, quality control is essential to ensure the continuing viability and genetic fitness of the biological control agents under production. This implies strict protocols for handling and standardization of diets and culture media. Thus, large-scale production of some biological control agents may be a complex process which must be carefully planned. For some agents this can mean a large initial investment in rearing facilities and continuous employment of well trained production staff. It is best adapted to situations where a farming community (large estates or communes) or a farming industry is able to undertake mass production of agents for a large area. History suggests that inundative and inoculative release programmes, once set up, are likely to continue by sheer momentum with little continuing assessment of their value. It is important that such assessments should be made regularly.

Evidence that augmentation, inoculation and inundation of parasitoids and predators is economically viable comes primarily from the private sector, where a number of quite successful small biological control businesses have been established. To date, these have been directed primarily at the control of glasshouse and citrus pests using parasitoids and predators, but there is much promise for expansion of such businesses to control pests in field crops. A particularly detailed analysis of chemical, cultural and biological control methods for the Mexican bean beetle, *Epilachna varivestis*, in the United States, for instance, has revealed that an inoculative control programme using a specific parasitoid gave higher benefit/cost ratios than any of 10 other possible control methods employing varying levels of insecticide application (Reichelderfer, 1981).1/

Microbial agents, applied in the same way as chemical pesticides are manufactured, formulated, stored and marketed as commercial products and so compete economically with their chemical counterparts. Several such products are being marketed by major suppliers of agricultural chemicals (notably *Bacillus thuringiensis* preparations) and many products with a restricted market are produced by small companies. However, many of these agents can be produced by cottage industries as is done in China. Economic evaluation and comparison with chemical control measures is more straightforward with these microbial agents as simple plot experiments can be undertaken using the same application method.

1/ In Papvizas (1981)
Conclusions

Biological control will have particular value in developing countries where traditional methods of chemical control are either prohibitively expensive (e.g., for subsistence farming) or over-exploited (e.g., conditions of high pesticide resistance). Introduction offers by far the greatest economy, as it incurs no recurrent costs, but augmentation, inoculation and inundation may prove economically competitive with chemical methods in many crop systems. In all cases, external costs of pesticide poisoning and environmental pollution are virtually eliminated by the adoption of biological control. Biological control is not incompatible with the continued use of pesticides and may be incorporated into an IPM system in a number of ways, but best results will be obtained in crops with only one or a few major pests, all of which can be controlled biologically.
Chapter III

BROAD ASSESSMENT OF BIOLOGICAL CONTROL POTENTIAL

It should be clear from preceding chapters that introduction is preferable to strategies which involve repeated release of control agents. However, successful introduction depends on complex, long-term interaction between agent and pest and results are more difficult to predict than in the case of a pesticide-like mass release to control one pest population at one time. Accurate predictions of the success of an introduction are very difficult but ecological theory allows us to make some general statements about when introduction will work and when alternative methods are likely to be needed.

Figure 1 represents a mathematical model which simulates a successful "classical" introduction. A pest population is initially at high, damaging levels in a crop, well above the threshold density where damage influences crop yield (dotted line). A predator or parasitoid is introduced which depresses the pest population below the economic threshold, and maintains it at a stable equilibrium level for generations to come. The key components of success are the level of depression (the final equilibrium must be below the economic threshold) and the subsequent stability (the pest population must not fluctuate so much as to cross the threshold). Three main factors will influence these components: the ecology of the pest, the kind of damage which it does and the cropping system it occurs in.

Pest ecology

Introduction is most successful against pests with moderate-to-low reproductive rates. It is convenient to think of pest reproductive rate as a force opposing the rate at which the control agents kill the pest. Therefore, higher rates of pest reproduction tend to raise the equilibrium level achieved after introduction. The control agent may still regulate the pest population, but it cannot now depress it as far, perhaps not even below the economic threshold. Thus, biological control must be thought of as a supplemental mortality aimed at pushing the pest population below the economic threshold.

The mobility of pest populations will also affect success. Those which are highly dispersive, such as armyworms and locusts, may colonize an area, exploit it to the limit, and then disperse. Their natural enemies are usually unable to influence the pest population before it has crossed the economic threshold. When the pest leaves, natural enemies populations decrease drastically and may even die out, leaving no effective defense against the next invasion. Such dynamically unstable interactions between pests and control agents largely rule out introduction as a viable strategy, and augmentation or inundation, coupled with a means for forecasting outbreaks, is recommended.
In this model, the pest population in the first generation is at an outbreak level (100) well above the economic threshold. The control agent (a parasitoid or predator) is introduced after ten generations. As its numbers increase from generation to generation, the pest population declines. Initial oscillations in both populations decrease with time to a stable equilibrium at which the pest population is depressed well below the economic threshold.
Pest Damage

Successful introduction requires that pest and control agent populations persist over time at low densities. Pests must therefore always be present in the crop because their complete elimination would lead to loss of the control agent population as well.

Pests which feed on the part of the crop which is harvested are referred to as 'direct pests', and those which damage other organs as 'indirect pests.' The economic threshold of direct pests is clearly much lower than with other pests and therefore they have to be held at a very low density to avoid unacceptable damage and so they are more difficult to control. Examples of such pests which have proved difficult to control are fruit flies, fruit boring moths, and cotton bollworms. By contrast, indirect pests such as scale insects, leaf miners and defoliators can usually be tolerated at a higher density except when they are disease vectors or the damage done by each individual is disproportionately great. The use to which the crop is put affects tolerance level - some damage may be tolerated when the crop is processed to provide a produce such as sugar or fruit juice, but not when the crop is marketed unaltered when the presence of feeding scars is unacceptable, as on fruit and vegetables, although much damage in this category is superficial and does not affect the nutritional value of the crop.

Cropping Systems

The permanence, or stability, of an agricultural system will have a great effect on the success of introductions for pest control. Highly unstable cropping systems include short-term cash crops, which may not exist in a particular area long enough to allow natural enemies to have an effect. Here the situation is very similar to that discussed for migratory pests; because pests appear intermittently (i.e. when crops are present), a long-term, stable interaction between pest and control agent cannot be established. The situation is less severe where short-term crops overlap in time within an area (e.g. tropical rice or brassica cultivation), as natural enemies may persist by moving from harvested crops to nearby new plantings. However, even under these conditions, short-term cropping which involves cultivation of the soil may disrupt biological control through destruction of resting stages of natural enemies in the soil or leaf litter.

Long-term plantation crops provide better conditions for introduction by ensuring the continuity of both the pest and control agent populations. The potential success of introduction in different cropping systems is summarized in the form of a rating system in Appendix A, from which the best kinds of crops for introduction can be calculated.

Environmental diversity will tend to favor persistence of natural enemy populations, by providing alternate prey or hosts and by providing other requirements, such as nectar and pollen sources. The overall value of natural vegetation around crops must, however, be balanced against its
role as a reservoir for pest populations. In some cases, it is valuable to encourage natural vegetation within crops. Ground cover in oil palm plantations is important to the conservation of parasitoids which attack a variety of moths damaging oil palm. Their importance was only discovered when herbicidal weed control was found to cause outbreaks of these pests.

To the extent that the proximity of natural vegetation is necessary to maintain populations of a control agent, the effectiveness of biological control will decrease as the area under a single crop is increased (i.e., extensive monocultures).

Control of Weeds

Much of what has been said for the control of insect pests also applies to the control of weeds. Insect control agents are relatively ineffective against plants which exhibit high reproductive rates and high 'mobility.' Annual weeds in short-term cropping systems have all of these attributes; they produce enormous amounts of seed which are widely dispersed, they grow very rapidly and are exposed for attack only over the brief duration of the crop. Because of this rapid growth and dispersal, introduced agents have little chance of controlling annual cropland weeds before they reach economically damaging levels.

Another important ecological factor in weed biological control is the amount of competition from other plant species. In rangelands, competition with grasses for light and water puts stress on weeds which enhances their susceptibility to insect attack. Without this competition, the impact of insect agents on weed populations is much reduced. Thus, where weeds grow in cultivated land (annual crop weeds) relatively free from competition, biological control will be more difficult.

Conclusions

The following general predictions arise from an ecological consideration of biological control. The strategy of introduction will be most effective against pests which:

(a) have a moderate to low reproductive rate

(b) are non-migratory

(c) are indirect pests of crops.

When these attributes do not apply, strategies of augmentation or inundation are more likely to succeed as short-term control measures for pest outbreaks.
Chapter IV

BIOLOGICAL CONTROL IN MAJOR CROPS

Crops with a substantial production in developing countries were selected from the FAO Production Yearbook for individual treatment. A scoring system (Appendix A) was developed to indicate the overall prospect for successful biological control, within the framework of IPM, based on the criteria discussed in the preceding section with weight given to those factors favoring stability and continuity of the habitat within and around the crop.

Long lists of insects, nematodes, weeds and diseases, have been recorded on crops, many of which are of negligible importance or only of local significance. Consequently, only the most important widespread pests, which are constraints on production over a large area, are emphasized but some pests with a restricted distribution, which are of critical importance in major production areas, are also included.

At present, plant diseases are best managed by developing resistant or tolerant crop varieties, by cultural methods and by sanitation. Research on biological control of diseases has recently increased.

Development of biological control of nematodes is even less advanced. No specific biological controls are available. Traditionally, certain plants, e.g. the African marigold, have been planted as a nematode control measure and it has been found that they secrete repellant substances into the soil. Some crops, including sesame, are reported to have a similar effect so that there is a possibility for the development of intercropping systems or rotations for the management of soil nematodes.

Specific biological controls of the annual weed species which invade arable land are not feasible at present because unless all species can be controlled by this means, herbicide application or hoeing is still required. Besides, the short lifespan of many of these weeds and their enormous seed production will make effective biological control difficult.

Storage pests require rigorous control, and tolerance levels are very low since even a small initial contamination with pests can lead to a devastating build-up by the time the produce is required. Furthermore, even a low infestation can render produce unacceptable. Consequently, biological controls are ruled out in bulk storage unless highly efficient microbial agents can be found which leave no residues detectable by the consumer and are completely non-toxic. However, in domestic storage by subsistence farmers where some infestation is tolerated, there may be opportunities for enhancing natural mortality.
Thus, most plant diseases, nematodes and also storage pests are not discussed as biological control is not yet practicable. Consequently, most space is given to insect pests, and other categories of pests are discussed only where there is a particular need. Certain insect pests of world importance in several crops or which are not directly linked to the crop environment (e.g. locusts) are treated separately, as are nonparasitic weeds. Where research needs for biological control can be identified, an indication of the cost is appended.

CEREALS

Wheat and Barley

These cereals are especially important in temperate and subtropical zone developing countries. They are chiefly grown by small farmers as short-duration crops in regions with a highly seasonal rainfall, and so are not an ideal target for most forms of biological control.

The major insect pest problem is a complex of aphids (Schizaphis graminum, etc.) which originated in the north temperate zone but is now widespread. During the last decade, concerted efforts were made by USAID to introduce parasitoids and predators from Europe and the Mediterranean basin into the southern cone of South America. Effective control has been reported from Chile, but further evaluation of the results is required before biological control is attempted elsewhere. These natural enemies should be effective under low intensity agriculture but more complex management systems will probably be needed where cultural methods are intensified and high yielding varieties are planted. Breeding of resistant varieties provides control of rust diseases (Puccinia spp.) which are the major disease problem, but the rapid emergence of new rust strains involves a continuous breeding programme. In most regions, seed-eating birds cause important loss in yield but no practicable biological control measures are known.

Rice

The recent intensification of rice culture by the expansion of irrigation and planting of new high yielding varieties has intensified pest problems in most major rice growing countries. Under traditional upland and rain-fed rice culture, pest problems are usually not limiting but the crop yield is low. Following intensification, Brown planthopper (Nilaparvata lugens) which is a vector of Grassy stunt virus and Ragged stunt virus; leafhoppers (Nephotettix spp.) which are vectors of Tungro virus and Yellow Dwarf virus; and leaf rollers (Cnaphalocrosis medinalis, Susumia exigua) have become of major importance in Southeast Asia and the Western Pacific region, while stem borers (Chilo spp., Scirpophaga spp., Sesamia spp.), which are the major pest under traditional culture, have declined in importance. Integrated pest management is now being developed in South and Southeast Asia under the FAO/UNEP Global Programme. Resistant varieties for suppression of brown plant hopper have been effective in the short term only. Studies on natural enemies within the FAO/UNEP scheme are planned but as yet no donor has been identified to fund them.
The biological control possibilities for leaf- and plant hoppers lie mainly in the conservation and augmentation of existing natural enemies but introduction of additional species may be indicated when surveys have been extended throughout the region. Haphazard introductions of parasitoids against stem borers have been made in a number of countries without beneficial results. Mass release of egg-parasitic wasps (Trichogramma spp.) have also been attempted, but with equivocal results. The overall prospects for biological control of stem borers of cereals and sugarcane require re-evaluation.

A further major pest of rice in parts of South and Southeast Asia and West Africa is gall midge (Orseolia spp.). The recent discovery that separate but similar species are present in these two regions means that a re-examination of the parasitoid complex is necessary to determine opportunities for biological control.

Diseases of rice are suppressed by breeding of resistant varieties. Prevention of spread of virus diseases is aided by control of their leaf- and planthopper vectors.

The minimum cost of implementing the proposals for a biological control input into the FAO/UNEP programme is estimated to be $75,000 per annum to support a single expert to work with the existing team. A special study on rice gall midge would require $150,000 over two years.

Tropical Dry Land Cereals

Maize, millets and sorghum are chiefly grown in areas with a short wet season and have many pest problems in common, notably a complex of stem boring moths and witchweed (Striga spp.). The stemborer problem is discussed under pantropical pests (pages 34 - 35).

Studies on witchweed in East Africa and India identified a number of promising natural enemies and there are indications of heavy insect attack in West Africa but no systematic study has yet been made there nor have serious attempts been made to exploit existing knowledge. Only partial control is likely using biological methods and the problem is so serious and so difficult to manage that control is unlikely to be achieved except in an integrated programme including breeding for resistance. The USDA is showing renewed interest in biological control of witchweed in the USA and may support further research.

A programme for biological control research in the Sahel Region of West Africa under the FAO/UNEP Global Programme on Integrated Pest Control for Basic Food Crops has been proposed by the CIBC costing $520,000 over a five-year period.

Maize

Where maize is grown as a subsistence crop, insecticide applications which can suppress insect pests are seldom practicable. Destruction
of residues after harvest can reduce stemborer carryover but is seldom enforced. Rotation, trap crops and hoeing can limit Witchweed attack but must be intensively pursued. No coordinated effort has been made to control aphids. In most regions, studies have been made on stemborers' natural enemies and some introductions of parasitoids have been made but with only limited success.

**Millet**

Millet is chiefly a crop of sub-desert regions where other cereal crops do not thrive and conditions are not ideal for biological control. However, the biology and natural enemies of the main stemborer pests are less well known than those of the other cereals so that base-line studies are required before the control prospects can be assessed. This is an objective of the FAO/UNEP programme for which proposals for an input costing $500,000 over five years have been put forward.

**Sorghum**

Sorghum is grown under conditions intermediate between those optimal for maize and millet. As well as stem borers and witchweed, there are important insect pests, midge (*Contarinia sorghicola*) and shoot fly (*Atherigona* spp.) which can be alleviated by synchronized planting and harvesting. The prospects for biological control of these pests do not appear to be good but ecological studies are needed to assess the possibilities for augmentation of their natural enemies.

**ROOT CROPS**

**Sweet Potato**

There is a single widespread major pest, the sweet potato weevil (*Cylas* spp.). Cursory surveys have not indicated promising biological control agents but thorough exploration at the centre of origin of this crop in South America is required before a final assessment can be made. The crop also suffers from a variety of defoliating moths and butterflies, as well as other weevils in particular locations. The biological control possibilities against these pests have not been investigated.

**Cassava**

Cassava had few major pests until the recent interest in the crop led to movement of germ plasm from continent to continent when green mites (*Mononychellus* spp.), mealybugs (*Phenacoccus manihoti*) and bacterial blight reached Africa from South America and became serious problems. The first two are targets for the introduction of control agents and have been intensively studied by the CIBC with support from IDRC. Biological control agents for mealybug were found, and experimental releases at IITA, Nigeria, produced very promising results. They are now being distributed to other affected areas. Predators of the mites were found and are available for trial. Other studies have shown that there are good prospects of developing varieties resistant to these introduced pest problems which will
supplement biological control of mealybug and mites. Mosaic viruses transmitted by whitefly (Bemisia tabaci) are important in South America and Africa. Tolerant varieties and clean planting material are important in mosaic management but further understanding of the whitefly problem would be an advantage (See under Pantropical Pests on page 34).

Strict quarantine is essential to protect Asia from the pests which reached Africa and to prevent other potential pests leaving South America.

**Potato**

As potatoes are mostly grown as a horticultural crop, they are included with vegetables (Page 30).

**GRAIN LEGUMES**

Many pest problems of grain legumes are common to more than one species. They include various species of beans, grams, soya bean, cowpea and pigeon pea. All except pigeon pea are short-term crops.

These conditions are not ideal for biological control by introduction but there have been some successes.

Parasitoids of the complex of podborers of pigeon pea in Trinidad were introduced into Mauritius where a substantial reduction in damage ensued. Some trials are now being made with these same agents in Fiji and Sri Lanka. Parasitoids of the bean fly (Ophiomyia phaseoli), a widespread pest in the Old World, were studied in East Africa and transferred to Hawaii where they provided good control. There is potential for further employment of these agents in Asia and the Pacific. In many areas, the pests and their natural enemy complexes on legume crops have not been studied so that further effort is required to assess the potential for biological control of other legume pests.

**OIL SEEDS**

**Groundnut**

This is the only oil seed crop which is grown on a large scale and which has been studied intensively. Groundnuts are subject to severe damage by the armyworms and cutworms (see Page 33). The other important insect pest problem is the cosmopolitan aphid (Aphis craccivora) which, in Africa, is the vector of rosette virus. Cultural methods give effective control of the virus.

**Castor**

In India where castor is extensively grown, it is subject to attack by the larvae of fruit piercing moths (Achaea spp.) which are troublesome defoliators. Biological control has been considered and some egg parasites were introduced, but their effect has not been assessed.
Sesame, Safflower, Sunflower,

Other oilseed crops are grown mainly by small farmers. Their pests and diseases have been little studied and few are of more than local importance. Consequently, no biological control studies are applied specifically against pests of these crops in developing countries.

PLANTATION CROPS

Sugarcane

This crop is effectively perennial in that it is ratooned and remains in the ground for up to six years. Because it is very difficult to treat with chemicals and it is usually not economic to apply them, biological control has been widely applied. Thus, in most areas, pest management relies almost entirely on biological controls. Stem borers are a major problem and much biological control effort against these pests has been undertaken in sugarcane. Parasitoids (Tachinidae) have been widely used within the New World and have provided control in parts of South America and the Caribbean. Since 1971, an Asian parasite (Apanteles flavipes) from India has been widely released in the New World and has given excellent results in the USA, Barbados, Brazil and elsewhere. However, in the Old World, biological control has not yet been successful except in Madagascar, and against one borer (Sesamia calamistis) in Mauritius. Campaigns involving inundative release of egg parasitoids (Trichogramma spp.) were widely used especially in the Caribbean, India and Taiwan, China, but although still favored by some workers, there is little satisfactory proof of their effectiveness. However, recent trials in India suggest that when applied in sufficient quantities under expert supervision, a reduction in damage can be obtained. White grubs (Scarabaeoidea) problems are also widespread. Parasitoids were introduced into many countries during the 1930's but with equivocal results. Now trials with insect diseases, which show a greater promise against these soil-inhabiting pests, are being made. Scale insects are important pests in some countries. Whitescale (Aulacaspis tegalensis) causes serious damage on the Indian Ocean islands and in Eastern Africa. Its natural enemies have been investigated and are used in Mauritius where unfortunately a full assessment is not yet available, and in Tanzania where a ladybird has provided excellent control. In India, no success has been achieved against another species (Melanaspis glomerata) but parasitoids from a related South American scale have been imported recently and are now being tested.

The importance of sugarcane mealybugs is uncertain but they have been controlled in Hawaii and parts of the Caribbean using ladybirds and a parasitoid from Africa.

A widespread leafhopper (Perkinsiella saccharicida) is a vector of Fiji disease. Biological control was carried out in Hawaii using egg predators which were also introduced into Mauritius as a precaution against Fiji disease reaching the island.
Hot water treatment of planting material, which is often employed for the control of fungal and virus diseases, is also effective against many insect pests. This technique, as well as cultural methods for the suppression of stem borers (stubble shaving, choice of varieties, removal of trash) are also useful in suppressing scale insects. However, there is a need for further research to find biological controls for the Old World stem borers and white grubs. Biological control should receive priority consideration when any new pest problems develop in this crop so as to avoid chemical treatments, as far as possible, which would adversely affect established management procedures.

Coffee

Commercial coffee chiefly comprises arabica (Coffea arabica) which grows best under cooler conditions, and robusta (Coffea canephora) which grows under more extreme tropical conditions. Of the two, arabica coffee is more susceptible to pests, and because of its higher value, its pests received more attention and pest management systems have been developed, notably in East Africa. Coffee has a particularly wide variety of important insect pests but most of them are restricted to a single continent. In Africa, Antestia bugs (Antestiopsis spp.), which transmit a fungus disease of the fruits, are the most important pests. Their natural enemies have been investigated, but there is little prospect for biological control, partly owing to the low economic injury threshold. Injudicious chemical applications against Antestia bugs have been responsible for outbreaks of leaf-miners (Leucoptera spp.) which have a large natural enemy complex. Related species of leaf-miners occur in most major coffee growing areas so that there is a prospect of exchange of natural enemies to enhance naturally occurring biological control. Only a single attempt has been made so far - a parasite from Dominica was transferred to Kenya but failed to parasitize the local species. Mealybugs are also widespread pests; Planococcus kenya was very successfully brought under biological control in Kenya by a parasitoid. Less success has been achieved to date with the Citrus mealybug (P. citri) which can be a troublesome pest, particularly in India. There, promising results have been obtained by inoculative release of a ladybird. Further study of this important pest of several tree crops is warranted to determine whether effective parasitoids exist to enhance suppression by predators.

The one African pest which has reached other continents is the coffee berry borer (Hypothenemus hampei), now an important pest in Central and South America, Indonesia and New Caledonia. Parasitoids from Uganda introduced into Brazil, Java and Sri Lanka during the 1930's, gave, at best, only partial control. Since then, an additional parasitoid has been discovered in the Ivory Coast, but its potential has not yet been tested. Biological control in central America, where it is a recent invader, has been proposed (cost $300,000), but no sponsor has yet been identified.

IPM was developed ad hoc in Kenya, making maximum use of existing and introduced natural enemies combined with a minimum of carefully supervised sprays. This work provides a model for coffee insect pest management in other areas. Yellow rust fungus (Hemileia vastatrix), now
widespread, can be effectively controlled by copper fungicide sprays but the improved leaf retention which results aggravates leaf-miner damage. Stringent quarantine is required to prevent the spread of coffee berry disease now widespread in Eastern Africa.

Tea

Outside the main Asian tea growing areas, pests are usually of minor importance with little action required except occasional pesticide applications against mites. Pest damage has been high in Sri Lanka where tortrix (Homona coffearia) was controlled by the introduction of a parasitoid from Java. For a time, this biological control was upset by chemical applications against shoot borers (Scolytidae), but they are now controlled by a revised pruning schedule.

In all tea growing areas, mosquito bugs (Helopeltis spp.) are troublesome. They are important as pests on other tree crops, but a solution of the problem would benefit tea growers also (see Page 34).

Cocoa

Cocoa suffers from a number of important fungus diseases, of which black pod (Phytophthora palmivora) is the most important. Recently, a parasitic fungus has been found in Brazil suppressing another fungus disease, witches broom (Crinipellis perniciosa). This parasite, also active against black pod, is now undergoing field trials as a control agent. This research gives the first promise of biological control of a tropical fungus disease complex.

In West Africa, the swollen shoot virus is important. No effective control is available but, transmission can be limited by control of its mealybug vectors (Planococcoides njalensis and other species) by manipulation of the ant fauna in plantations to favor predatory species which eliminate mealybugs and other pests.

Mosquito bugs are frequently the most important pest of cacao. No satisfactory control is available but treatment with persistent insecticides and predatory ant management can be helpful.

Pod moth (Acrocercops cramerella) is an increasing serious problem in the island archipelagoes adjoining Southeast Asia, particularly Indonesia, the Philippines, and most recently in Sabah. Control can be obtained by strictly enforcing a closed season when pods are stripped from the trees and by plantation hygiene. Biological control, which is desirable to provide more easily enforced long-term control, will involve an investigation of its origin and alternative hosts.

Coconut

Coconuts are grown under a wide variety of conditions from scattered semi-wild palms which receive little or no husbandry, to
intensively managed estates. Much biological control has been done on this crop which is subject to attack by a large number of insect pests. It was pioneered in Fiji where two native leaf-feeding pests were controlled by importation of parasitoids from other islands. Equally successful control of one of them, a beetle leaf-miner (Promecotheca spp.), has also been obtained using the same parasitoids on other islands in the region and recently in Sri Lanka. Other moth defoliators cause periodic outbreaks which are terminated by natural enemy action, but careful management, as with the similar problem in oil palm, can reduce the frequency and severity of outbreaks.

Rhinoceros beetles (Oryctes spp.) are serious pests of coconuts and other palms in most parts of the Old World. After many years of experimentation, biological control was eventually obtained in the South Pacific by the combined action of a virus and fungus disease. Trials in the Seychelles against a related rhinoceros beetle give promise that the virus can be used more widely. Control of rhinoceros beetle is also valuable in reducing attack by palm weevils (Rhynchophorus spp.). In Central and South America, they are vectors of red ring disease which is caused by a nematode (Rhadinaphelenchus cocophilus).

Scale insects (particularly Aspidiotus destructor) are pests of coconuts in all areas. Biological control has been achieved when required by introduction of ladybird predators.

Bugs (Ambypelta spp. in the Solomon Islands; Pseudotheraptus wayi in East Africa) are a cause of immature nut fall. Techniques for controlling these bugs by manipulation of the ant fauna of coconut plantations have been worked out but there is a need to test their practical value on an adequate scale.

Damage to young nuts is also caused by a mite (Aceria guerreronis) on the Atlantic coasts of Africa and the Americas. A fungus disease has been isolated which offers the only opportunity for effective control of this problem. An estimated $150,000 is needed to finance field trials.

The results outlined indicate that integrated management of coconut pests relying on biological control and supplemented by manipulation of the ground cover to enhance and maintain it is practicable and economical. Assistance in developing IPM has been requested by Indonesia; proposals lie with the FAO but a donor agency has not yet been identified. About $70,000 is needed for preliminary assessment.

Oil Palm

Many coconut pests — rhinoceros beetles, palm weevils and red ring nematode — also affect oil palms but are usually less serious in this crop.

Defoliators (Psychidae, Limacodidae) can be troublesome especially in Southeast Asia. A management system has been developed in
which the ground cover is manipulated to enhance natural enemy action and when necessary this is supplemented by localized spraying with a virus which maintains natural biological control. Similarly, in West Africa and South America, leaf miners (Hispinae) cause important damage to the leaves and should be susceptible to the same kind of management techniques.

Insecticide application to oil palms should be avoided because discoveries in West Africa show that certain weevils (Elaeidobius spp.) are pollinators of oil palm in West Africa. Introduction of one of the weevils into Southeast Asia, has increased yields by about 20%, and has saved money through the abandonment of hand pollination.

Rubber

Rubber is remarkably free from serious insect pests. The most important problems are diseases, which are controlled by fungicides and resistance breeding. Strictly enforced quarantine is also essential in the Old World to prevent accidental introduction of South American leaf blight (Microcyclus ulei).

Tobacco

Because of the requirement for undamaged leaves, it is difficult to avoid reliance on pesticides for control of tobacco pests. Although, many are pests of other crops and their control on these crops would also benefit tobacco growers, biological control has not been developed specifically against tobacco pests. The most serious include budworms (Heliothis spp.) and whitefly (Bemisia tabaci) which are discussed under Pantropical Pests on page 34. Progress has been made with biological control in a number of countries.

In parts of Africa and Asia, the parasitic weed, Broomrape (Orobanche spp.) is a serious problem. It is controlled in the USSR and part of Southeast Europe by augmentative releases of a native stem mining fly. Trials are needed to assess the value of this fly for biological control in other areas, both by augmentation in those where it is already present and by introduction in India and other places where it does not occur naturally. Dollars fifty thousand spent over two years on laboratory and field work would enable such an evaluation.

FIBRES

Cotton

Cotton must be grown as an annual to avoid build-up of certain of its many important pest problems. The pest complex varies from region to region and management systems, largely based on conserving native natural enemies and reducing, as far as possible, pesticide application, are being developed. This has become urgent because cotton growing has become overdependent on pesticides; one consequence is the upsurge of whitefly (Bemisia tabaci) which has reached catastrophic proportions in Turkey, the Sudan and Nicaragua.
The key pests of cotton are usually bollworms which include Heliothis spp., a pest of world importance. Closed seasons and cultural controls especially against pink bollworm (Pectinophora gossypiella) are useful. Plant breeding has produced varieties resistant to other pests (notably jassids) and diseases.

The FAO/UNEP Global Programme includes major projects for IPM in cotton which need to be supplemented by special studies on whitefly and Heliothis. Natural enemies of other cotton insect pests are relatively well known in most areas, but the information needs to be collated and assessed to identify the most promising natural enemies for augmentation and introduction as an extension of the present FAO activity. This, with reduced pesticide usage, will open the way for IPM making maximal use of biological control opportunities.

VEGETABLES

Most vegetable crops are grown on small areas and are subject to pests too numerous to be reviewed in detail, but there are a number of pests common to several crops worldwide.

Successful vegetable growing has become dependent on pesticides, but in areas where vegetable growing is extensive, there is an opportunity for IPM to reduce pesticide usage, given the cooperation of growers and education of consumers to accept a few blemishes. Introduction of microbial agents applied as sprays or seed dressings, combined with rotations and modification of cultural practice, are a desirable preliminary to the introduction of other biological controls. The natural enemies of many major pests have been studied, and biological control demonstrated under experimental conditions. Major pests which are discussed separately are whitefly, Heliothis, armyworms and cutworms. Another major pest, the giant African snail (Achatina fulica), has been spread from East Africa to most countries bordering the Indian and Pacific Oceans. Biological control using predators has been attempted and has achieved limited success on some islands but is not favored by conservationists in many countries because the predators indiscriminately attack native snails, as well as the target pest. Further surveys and research are required to ascertain if any specific diseases or parasitoids of the giant African snail are present in East Africa which could be exploited elsewhere. Dollars twenty-five thousand would cover the cost of an intensive survey to determine the possibilities.

Potato

Biological control of potato tuber moth (Phthorimaea operculella) has been attempted in many countries. Good results are reported from Cyprus and Zambia. They remain to be evaluated in India, Mauritius, Madagascar and St. Helena. With this experience, there are opportunities for further attempts in other countries and renewed effort where biological control has not been fully effective, concentrating on those parasitoids which have been most successful to date.
Cabbage and Other Brassica Crops

The most widespread and damaging pest of brassicas is the diamond back moth \((Plutella xylostella)\). Its natural enemies are well studied and biological control has been demonstrated. It is usually not used because other moth pests have to be controlled with chemicals at present. Studies to identify biological control agents for these are needed. In the interim, bacterial agents based on \(Bacillus thuringiensis\), properly applied, can minimize the need for synthetic pesticides.

FRUITS

The pests of fruits are so diverse and many fruit crops are grown on such a small scale that detailed treatment is only feasible for major cash crops. Fruit flies are a worldwide problem requiring solution (Page 35).

Banana

The scale and intensity of banana culture vary from subsistence cropping as a staple food to large-scale estates producing dessert bananas for export. Biological control of the widespread banana weevil \((Cosmopolites sordidus)\) has been explored. Predatory beetles \((Histeridae)\) have been introduced in many places but are largely ineffective. On the whole, there are few prospects for biological control, particularly in large estates, but in Southeast Asia and the Pacific, where culture is less intensified, there are a number of locally important pests for which biological control may be feasible but has not been fully explored. These include the banana aphid \((Pentalonia nigronervosa)\), the vector of bunchy top virus, for which biological control is required in India.

Citrus

Citrus is affected by a large and diverse assemblage of insect pests. The many species of scale insects, mealybugs and whiteflies have effective parasitoids which are now widely applied, and where this is done, pesticide-induced problems have abated. There remains a need to control fruit flies which can be suppressed in orchards by bait sprays which do not affect beneficial insects. Only occasional sprays are now needed in most areas against other pests. In Africa, the most important of these is the false codling moth \((Argyroploce leucotreta)\). Where feasible, removal of fallen and damaged fruit, rigorously applied, can provide effective control, and research is being carried out in South Africa to develop inundative control using mass-produced egg parasites.

Pineapple

The only major insect pest problem on pineapple is mealybugs \((Dysmicoccus brevipes)\) which are very difficult to control as they are concealed from natural enemies and contact pesticides. Biological control has so far failed except in Hawaii, where some improvement is reported, but further research may detect more effective natural enemies.
Apple

The apple woolly aphis (*Eriosoma lanigerum*) has spread to most parts of the world and has been brought under control in most areas by introduction of a parasitic wasp. Unfortunately, it does not attack aphids on the roots and, where breeding underground is substantial, biological control has only been partially successful. In Eurasia, the key pest is the codling moth (*Cydia pomonella*), and where chemical control has been carried out, pesticides have upset natural biological control. Microbial control of codling moth is being developed as an alternative and provides the best prospect for avoidance of chemical treatments. Meanwhile in some areas, pesticide-resistant mite predators have appeared and are making an important contribution to IPM.

Date

Biological control of date palm scale (*Parlatoria blanchardi*) in North Africa has been achieved by introducing ladybirds. The principal pest in the Arabian Gulf states is the Dubas bug (*Omastrissus binotatus*); biological control has been proposed but research has not yet been initiated. Avoidance of chemical treatments is desirable as they can only be effectively applied from the air and so cause widespread pollution, upset natural control of insects on crops beneath the palms and kill bees kept for honey production.

NUTS

The most important nut crop in developing countries is cashew. The principal pest is mosquito bugs.

FORAGE

Lucerne

Lucerne, or alfalfa, is often irrigated and cut repeatedly over a period, and so provides opportunities for biological control. Providing it is harvested in strips on a rotation and not clean-cut, natural enemies build up and move into the uncut crop, and usually provide satisfactory protection. In the Southern Hemisphere, where the major aphid pests are not native, introduction of natural enemies of proven value, combined with strip cutting, gives very effective control.

Pastures

In pastures, locusts, armyworms and cutworms can cause important damage. The Rhodes grass scale (*Antonina graminis*) became a serious pest in parts of the New World, but spectacular control has been obtained using a parasitoid introduced from India.

The most important pest problem is usually invasive woody weeds. Biological control of a number of these has been achieved and many others (except grasses and sedges) are good targets.
MAJOR PEST PROBLEMS AFFECTING SEVERAL CROPS

The following are some problems which will be best dealt with on an individual pest basis rather than in the context of biological control for a particular crop, as they affect several crops, and control in one only would not solve the problem as a whole. Many of these problems are also extremely widespread and need to be approached on a regional basis.

Migratory Pests

Migratory insects pose a special problem in that the source may be remote, sometimes in sparsely inhabited areas, and best dealt with before the crops are invaded. This will often require collaboration between countries, as with the FAO-directed effort against the Desert locust covering the entire area between Mauritania and India.

(a) Locusts and grasshoppers. The source areas of the major locust species are now defined, which allows monitoring and suppression of potential outbreaks by chemical means and, in some instances, modification of the habitat so that outbreaks are prevented. However, grasshoppers and, on occasion, locust swarms are still important sources of crop loss. Studies of their natural enemies have identified only a few opportunities for biological control. The most promising is a protozoan disease (*Nosema locustae*), which has been applied effectively in bait on the US prairies. Trials in tropical countries are needed to test its effectiveness under different conditions. It is likely that this will show that further research is needed to develop formulations which will maintain viability of disease spores under high temperature storage in the field and from exposure to intense sunlight and desiccation.

Some possibilities exist for attempting to enhance parasitoid and predator action by introductions into isolated areas where the natural enemy complex is deficient. This approach has provided control of the rice grasshopper (*Oxya chinensis*) in Hawaii.

(b) Armyworms and cutworms (*Spodoptera* spp., *Plusia* spp., *Agrotis* spp.). Some moth pests are highly mobile and may migrate long distances. In addition, armyworms aggregate to produce swarms which are the cause of sudden outbreaks in pasture and rangeland which, in turn, may invade crops such as maize and sorghum. As with locusts, control is difficult and depends upon identifying source areas so that preventative action can be taken. Bacterial and viral preparations offer an alternative to insecticides but still require development before widespread application under tropical conditions will produce consistent good results. An introduced parasitoid has been completely effective against one species (*Mythimna separata*) in New Zealand which suggests that other opportunities for classical biological control may exist; further investigation is required to identify them.
Some progress has been made in suppressing *Spodoptera* spp. in vegetable crops in the Caribbean using an egg parasitoid. Further studies are required to test other egg parasitoids so as to identify the most efficient species and provide improved control elsewhere. This could be done at a university or research institute by comparing samples gathered from a number of regions at a cost of about $20,000. Preliminary studies in Uganda show that in some places, these and similar pests are always very scarce, possibly through parasitoid action, so that there remains a need for further exploratory work in selected areas to provide additional control agents, if the supposition is verified.

**Pantropical Pests**

Some insect pests are now virtually cosmopolitan or comprise a succession of closely allied species which cover a great part of the world. Many of these are very serious pests of a number of different crops, and although they have been extensively studied, there is a need for collation and appraisal of the results so far. Additional research to fill gaps in knowledge and concerted effort in several countries to improve control measures is required as follows:

(a) **Whitefly** (*Bemisia tabaci*). This insect affects most vegetable crops, is a vector of a number of important virus diseases — notably in cassava — and has become a catastrophic pest on cotton following over-use of insecticides. Its biology is incompletely studied. Very little is known of its ecology, including natural mortality factors, except on the cotton plant. As it attacks a wide range of crops and breeds on many species of weeds in and around fields, a comprehensive approach to control is required. Therefore, bio-ecological studies are needed, especially in its area of origin (Southeast Europe, Pakistan) to identify natural enemies and other factors which may prevent outbreaks and to develop means of exploiting them. About $200,000 would be needed for preliminary studies over three years, together with laboratory and field testing of potentially useful natural enemies.

(b) **Mosquito bugs** (*Helopeltis* spp. and related genera). On each continent, woody crops, including cotton, are affected by mosquito bugs. They are extremely damaging at low density because feeding produces severe distortion of plant growth. Little is known of their ecology except in cocoa plantations in West Africa. There is a possibility that effective natural enemies exist in some regions, but studies are needed in South America and Indoensia-New Guinea before the opportunities can be assessed. A two-year survey by two entomologists would cost about $200,000.

(c) **Heliothis**. One or more species of *Heliothis* are serious pests on each continent. They affect a range of crops and wild plants
which act as a reservoir for infestation of the others. Thus, they are cotton bollworms, corn earworms, tobacco budworms, legume pod borers and pests of vegetables, notably tomatoes. Although much is known of their biology on some crops in some locations, little reliable quantitative data exists so that studies are needed to identify ways of enhancing the action of existing natural enemies and identifying opportunities for supplementing them, as recommended at a special Workshop held at ICRISAT in late 1981. A cost of $50,000 per entomologist per year would be incurred, and the overall cost would depend on the scale of activity and geographical coverage.

(d) Stemb borers of cereals and sugarcane. In each region, a complex of pyralid (Chilo spp. etc in the Old World, and Diatraea spp. in the New World) and noctuid (Busseola spp. in Africa and Sesamia spp. in the Old World) moths is present. Most species are pests of several crops - most are native and maintained by breeding in wild grasses, as well as crops. Much is known of their natural enemies, and considerable progress has been made in the biological control of the New World species using native parasitoids and a wasp (Apanteles flavipes from Asia). Attempts to achieve biological control have been made from time to time in the Old World using parasitoids from the Americas and exchanges of species between Asia and Africa; but limited success has occurred in Mauritius and Madagascar only. Therefore, a wide-ranging collaborative programme is required to screen the more promising parasitoids, explore indications that host preference can be changed during laboratory breeding and to undertake world planned field trials.

(e) Fruit flies. Fruit flies are a serious problem in most tropical and warm temperate countries; the problem is aggravated by accidental introductions and because they breed in wild fruits beyond the reach of pesticides. Biological control has been attempted, but except in Hawaii the results have been disappointing. Some success in eradicating fruit flies has been achieved using sterile male techniques against invading species in Mexico and throughout Pacific Islands, but because of the very high cost, it is not feasible to use these methods against long-established species in continental areas. Besides, there remains the risk of reintroduction. Further biological control effort is justified but requires more intensive study of each problem under the conditions where control is required and more critical choice of biological control agents adapted to local conditions.

(f) Termites. Crops grown in dry areas, especially tree crops, can be severely damaged by termites. Conventional biological control is not feasible at present. Behavioural chemicals seem to provide a more likely solution without recourse to broad spectrum pesticides.
Annual weeds in arable land are poor targets for biological control because of the large number of species which must be controlled together. Hoeing is the most appropriate non-herbicide control for these weeds. Parasitic weeds, of which the most important are witchweed (Striga spp.) on cereals, and broomrape (Orobanche spp.) on tobacco, have been discussed in the sections on appropriate crops. Others are mistletoes (Loranthaceae) and dodders (Cuscuta spp.) which have also received study but have not been subject to concerted effort at biological control. Biannual and perennial weeds, especially those in pastures, rangeland and plantations, are good targets, particularly when a single species has become dominant. Floating water weeds, which cover the surface of dams and irrigation channels, are also good targets. Tropical weeds and some widespread temperate weeds for which biological controls are available are listed.
(a) **Tropical Terrestrial Weeds**

Black sage (*Cordia curassavica*). Excellent control in Mauritius, promising results in Malaysia and Sri Lanka.

Harrisia cactus (*Eriocereus martinii*). Very promising results in Queensland.

Prickly pear cactus (*Opuntia* spp.). Excellent control in Queensland, good to excellent results in many other countries, few poor results.

Pamakani (*Ageratina riparis*). Promising results in Hawaii.

Mile-a-minute (*Mikania micrantha*). Insect agents available for trial. Affected areas - India, Southeast Asia, Indonesia.

Koster's curse (*Clidemia hirta*). Effective control in open pasture in Fiji, Hawaii.

Emex (*Emex spinosa*). Good results, Hawaii.

Lantana (*Lantana camara*). Good results in Hawaii and one area of Uganda, some progress in Queensland. Renewed effort required elsewhere as first introductions not effective.

Puncture vine (*Tribulus* spp.). Good to excellent results in USA, Hawaii, St. Kitts.

Broomrape (*Orobanche* spp.). Native fly being used to some effect in Southeast Europe, USSR. Trials in India proposed.

(b) **Tropical Water Weeds.**

Alligator weed (*Alternanthera philoxeroides*). Effective control by insects in USA and Queensland.

Water hyacinth (*Eichhornia crassipes*). Promising results, USA, Queensland. Good prospects in Sudan. Being taken up in several other countries.

Water fern (*Salvinia molesta*). Effective control in Lake Kariba. Excellent Initial results in Queensland. Being taken up in several other countries.

Water lettuce (*Pistia stratiotes*). Mass releases of a native moth clear infestations in Thailand. Indications that more effective agents can be found in South America and possibly Africa.
Submersed weeds. Fish, especially grass carp (Ctenopharyngodon idella), useful in dams and fish ponds. Now used or under trial in many countries.

(c) Selected Temperate Zone Weeds

Thistles (Carduus spp. & Cirsium spp.). Promising early results in North America and New Zealand.

Knapweeds (Centaurea spp.). Good potential with agents now being colonized in North America.

Skeleton weed (Chondrilla juncea). Good control of some varieties in Australia and California. Agents adapted to other varieties actively being sought.

Ragwort (Senecio jacobaea). Control in parts of North America good, but results disappointing elsewhere. Other agents now being colonized in North America and Australia.

St. John's wort (Hypericum perforatum). Excellent to satisfactory results in North America, Australia, Chile, New Zealand and South Africa.

Blackberries (Rubus spp.). Rust fungus effective against some species in Chile. Strains being selected for trial in Australia.
Conclusions

From a foundation in the methods and success of biological control (Chapter 1), its implementation and cost (Chapter 2) and its probability of success (Chapter 3), we have developed in this chapter specific priorities for biological control programmes in the major crops of developing countries. Emphasis has been placed on prospects for increased use of biological control in the immediate future.

Prospects for long-term control through introductions and conservation are best in plantation crops which provide a stable environment, and much has already been done in some crops, notably in sugarcane, coconut and citrus. Introductions should be more widely applied. Applied research is still needed against pests such as stem borers and white grubs in sugarcane, berry borer, leaf miners and mealybug on coffee, and leaf miners on oil palm. Perennial weeds of pastures are also promising targets. Although not ideal targets, further concerted effort is needed against fruit flies and mosquito bugs for which there are no really satisfactory control measures. Prospects are less good for introduction in annual cropping systems, but the importance of certain pests there and the cost or difficulty of chemical control for some of them points to a clear need for investigating biological methods. Amongst these pests, whitefly, stem borers, Heliothis and various defoliating moth larvae are of particular importance. In addition to introduction and conservation, studies in annual cropping systems should investigate methods for inoculation, augmentation and inundation of control agents.

Long-term controls can be of benefit applied singly but, it is better to apply them as part of overall management. With short-term controls, the IPM approach will be essential to obtain benefits where current practice relies on heavy pesticide usage.

Detailed appraisals and plans of action with costings for particular crops or systems can only be developed for specific situations.
The following provide detailed treatment of the examples mentioned in the text (*) or more extended discussion on aspects of biological control theory and practice.


Appendix A

CHOICE OF CROP AND ASSESSMENT OF THE PROBABILITY FOR SUCCESS OF DIFFERENT APPROACHES TO PEST CONTROL

As noted in Chapter IV, the crops treated in detail are those for which there is substantial production in developing countries, as indicated by the FAO Production Yearbook 1980. They are listed in the accompanying table with an assessment of their suitability for the different approaches to biological control outlined in Chapter I.

This assessment was made by deriving a scoring system based on the conclusions of Chapter III in which it is shown that stability of the habitat in space and time favor long-term biological controls and that the larger the area occupied, the greater the chance of stability and persistence of populations of organisms. These criteria are independent of the inherent attractiveness of the crop plant itself to colonization by pests (e.g., rubber attracts few insects, but cotton has many insect pests), and so do not reflect the number of opportunities for biological control on a particular crop. The chances of success against a particular pest are determined by other criteria discussed in Chapter III.

The score for each of the four key factors is graded 0 - 3, with a higher score indicating increasing chance of achieving long-term biological control, as follows:

**Climate**

<table>
<thead>
<tr>
<th>Category</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme</td>
<td>0</td>
</tr>
<tr>
<td>Highly seasonal</td>
<td>1</td>
</tr>
<tr>
<td>Moderately seasonal</td>
<td>2</td>
</tr>
<tr>
<td>Uniform</td>
<td>3</td>
</tr>
</tbody>
</table>

**Duration of crop**

<table>
<thead>
<tr>
<th>Category</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-term</td>
<td>0</td>
</tr>
<tr>
<td>Medium-term</td>
<td>1</td>
</tr>
<tr>
<td>Long-term</td>
<td>2</td>
</tr>
<tr>
<td>Permanent</td>
<td>3</td>
</tr>
</tbody>
</table>
### Scale of planting

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scattered</td>
<td>individual or small groups</td>
<td>0</td>
</tr>
<tr>
<td>Small</td>
<td>small-holder plots</td>
<td>1</td>
</tr>
<tr>
<td>Medium</td>
<td>large farms</td>
<td>2</td>
</tr>
<tr>
<td>Large</td>
<td>estates, irrigation schemes, communes, etc.</td>
<td>3</td>
</tr>
</tbody>
</table>

### Husbandry

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intense</td>
<td>soil cultivated, no weeds</td>
<td>0</td>
</tr>
<tr>
<td>Moderate</td>
<td>regular clean weeding</td>
<td>1</td>
</tr>
<tr>
<td>Low</td>
<td>occasional hoeing or slashing</td>
<td>2</td>
</tr>
<tr>
<td>Negligible</td>
<td>essentially unweeded</td>
<td>3</td>
</tr>
</tbody>
</table>

As the conditions under which crops are grown are not uniform, a range of scores is obtained for each. A low range of scores indicates that biological control techniques with only a short-term benefit are most likely to succeed (i.e. inundation, augmentation, microbial agents used as pesticides, etc.). A high score indicates that, as well as techniques with a short-term benefit, a long-term benefit is also likely to succeed (i.e. "classical" biological control). These distinctions are not absolute as long-term results have been obtained in situations where the score is low.

The table also includes estimates of the number of species of insect pests against which biological control has been attempted and the number against which it has succeeded in at least one location. These figures substantiate the scoring method, as crops with a higher score have a higher proportion of successes - 35% for crops with a mean score less than 8, and 44% for those with a mean more than 8. The difference is much greater if all attempts are included because many tree crop pests have been controlled successfully in a number of countries, e.g. cottony cushion scale in at least 38 countries; apple woolly aphid in at least 30 countries, and one ladybird (*Cryptolaemus montrouzieri*) is used in at least 32 countries for mealbug control.
CROP SUITABILITY ASSESSMENT FOR BIOLOGICAL CONTROL

<table>
<thead>
<tr>
<th>Crop</th>
<th>Score</th>
<th>Number of pests 1/</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Attempted</td>
</tr>
<tr>
<td>CEREALS</td>
<td></td>
<td>2-5</td>
</tr>
<tr>
<td>wheat &amp; barley</td>
<td></td>
<td>3-6</td>
</tr>
<tr>
<td>rice</td>
<td></td>
<td>2-5</td>
</tr>
<tr>
<td>maize</td>
<td></td>
<td>1-4</td>
</tr>
<tr>
<td>sorghum</td>
<td></td>
<td>1-5</td>
</tr>
<tr>
<td>ROOT CROPS</td>
<td></td>
<td>3-7</td>
</tr>
<tr>
<td>sweet potato</td>
<td></td>
<td>5-10</td>
</tr>
<tr>
<td>cassava</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRAIN LEGUMES</td>
<td></td>
<td>1-5</td>
</tr>
<tr>
<td>beans, cowpea, soya</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OIL SEEDS</td>
<td></td>
<td>3-6</td>
</tr>
<tr>
<td>groundnut</td>
<td></td>
<td>3-8</td>
</tr>
<tr>
<td>castor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sesame, safflower,</td>
<td></td>
<td>3-6</td>
</tr>
<tr>
<td>sunflower</td>
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<td>PLANTATION CROPS</td>
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<td>sugarcane</td>
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<tr>
<td>coffee arabica</td>
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<td>8-11</td>
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<tr>
<td>robusta</td>
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<tr>
<td>tea</td>
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</tr>
<tr>
<td>cacao</td>
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<td>7-12</td>
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<tr>
<td>coconut</td>
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<td>9-12</td>
</tr>
<tr>
<td>oil palm</td>
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<td>2-5</td>
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</table>

1/ The number of species of insect pests against which "classical" biological control has been attempted and the number of species which have been successfully controlled in at least one location.
<table>
<thead>
<tr>
<th>Score</th>
<th>Number of Pests</th>
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<tr>
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<tr>
<td>VEGETABLES</td>
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<td>brassicas</td>
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<td>potato</td>
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<td>FRUITS</td>
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<td>banana</td>
<td>7-12</td>
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<td>pineapple</td>
<td>3-8</td>
</tr>
<tr>
<td>citrus</td>
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<tr>
<td>apple</td>
<td>4-11</td>
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<tr>
<td>date</td>
<td>1-9</td>
</tr>
<tr>
<td>NUTS</td>
<td></td>
</tr>
<tr>
<td>(cashew, pistacio, etc)</td>
<td>5-12</td>
</tr>
<tr>
<td>FORAGE</td>
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<tr>
<td>lucerne</td>
<td>4-9</td>
</tr>
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<td>pastures</td>
<td>8-12</td>
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</tbody>
</table>
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