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Biological control of insect pests by insect parasitoids and predators: the BIOCAT database

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ABSTRACT

The structure of the BIOCAT database, which contains records of the introductions of insect natural enemies for the control of insect pests worldwide, and is now available online, is explained. It is a useful summary of biological control effort and a guide to factors which may influence the success of introduction programmes, but is not detailed enough for making firm predictions.

INTRODUCTION

The results of introductions of agents for classical biological control are of great interest, not only to biological control practitioners, but also to ecologists interested in biogeography and the process of colonization by invading species, to taxonomists who may encounter unfamiliar species and to conservationists concerned with their impact on native biota.

Much relevant information has been gathered in reviews of classical biological control programmes, notably the world review edited by Clausen (1978) and the series of reviews, chiefly of activities in Commonwealth countries, published by the Commonwealth Institute of Biological Control, now the International Institute of Biological Control, since 1960 (Table 1). Reviews of biological control attempts have also been published for a few important pest species (Table 2). The compilation of these reviews has prompted the authors and others to analyse the data and attempt to draw generalizations concerning the process and conduct of classical biological control or to use the information to support ecological concepts and hypotheses. To aid this, computerized databanks have been an obvious tool and have been used to extract summary data for further analysis, notably, Hall and Ehler (1979) developed a databank from the information in Clausen (1978).

The BIOCAT database began as a card index from Clausen (1978) and the CIBC reviews and has been extended in an attempt to include all records of introductions up to 1990, drawn as far as possible from reviews and supplemented by information from other publications, particularly for the periods following the cut-off dates of reviews for regions or particular pests. It now contains 4769 records and a version has been put on line by the Microbial Strain Database Network (MSDN) for users of the Information Resource for the Release of Organisms into the Environment (IRRO). Reference to BIOCAT has also been made in a number of publications by staff of the IIBC, which has elicited enquiries about the database. It is therefore appropriate to provide a description of the database and a summary of its contents, with some comments on its value as a research tool as well as a record of classical biological control of insect pests.

THE BIOCAT DATABASE

BIOCAT contains records of the introduction of insect natural enemies, parasitoids and predators, for the control of insect pests. It does not include the introduction of other natural enemies for insect control such as pathogens, nematodes, arachnids and vertebrate predators. Also excluded are introductions into greenhouses and other protected cultivation where the agent was not expected to survive outdoors, or introductions of dung beetles and other insects primarily for dung disposal and only secondarily to suppress dung breeding flies. However, it is hoped to expand the database at a later date to include all introductions of biological control agents for controlling arthropod pests.

The database was compiled on a personal computer using the dBaseIV program. Each record consists of thirteen fields which are described in the following paragraphs.

Pest. The scientific name of the pest, which has been updated from the source document where appropriate using the preferred names in the CAB International Arthropod Name Index (ANI Database; Wood, 1989). When an agent was released against more than one pest only the principal target is entered in this field.

Other Pest. This field lists other pests against which the agent was liberated during the period when releases were made against the main target pest.

Classification of pest. The order and family of the pest named in the pest field is given, except that the orthopteroid orders are all entered as "Orthoptera" because there are only a few records each for Orthoptera *sensu stricto* and Phasmida and Dictyoptera. The usage "Hemiptera" and

Table 1. Major reviews containing records of introductions of insect agents for biological control of insect pests

Area	Dates	Reference
WORLD		
World	-1965	Clausen 1978
World - Hymenoptera	-1980	Luck 1981
AFRICA		
Afrotropical Region	-1970	Greathead 1971
Cape Verde Islands	-1982	Lobo Lima & van Harten 1985
	1983-1987	van Harten *et al.* 1990
Ethiopia	1946-71	Haimanot & Crowe 1979
AMERICA CENTRAL & SOUTH		
Latin America	-1988	Altieri *et al.* 1989
Chile	-1958	Marco 1959
	1902-83	Zuñiga 1985
Brazil	-	Melo 1990
Ecuador	-1988	Koch 1989
British Caribbean	-1982	Cock 1985
AMERICA - NORTH		
Bermuda	-1982	Cock 1985
Canada	-1958	McLeod *et al.* 1962
	1959-68	Canada 1971
	1969-80	Kelleher & Hulme 1984
USA	-1965	Clausen 1978
USA - Hymenoptera	-1982	Sailer 1983
ASIA		
South	-1969	Rao *et al.* 1971
India	1969-73	Sankaran 1974
Malaysia	-1978	Ooi *et al.* 1979
Pakistan	-1980	Mohyuddin 1981
AUSTRALASIA		
Australia	-1959	Wilson 1960
New Zealand	-1987	Cameron *et al.* 1989
EUROPE and MEDITERRANEAN		
Egypt	-1950	Kamal 1951
France	-1985	Jourdheuil 1986
Israel	1905-65	Rivany 1968
	1971-78	Wysoki 1979
	1976-87	Argov & Rossler 1988
Poland	1959-75	Lipa 1976
	1976-85	Pruszynski 1989
USSR	-1985	Izhevskii 1988
Western and Southern Europe	-1975	Greathead 1976
PACIFIC		
Cook Islands	-1978	Walker & Deitz 1979
Fiji	-1969	Rao 1971
	1969-78	Kamath 1979
Hawaii	-1963	Pemberton 1964
	-1983	Lai & Funasaki 1983
Mariana Islands	1911-88	Nafus & Schreiner 1989
South Pacific	-1969	Rao *et al.* 1971
	-1971	Cochereau 1972
Papua New Guinea	-1959	Wilson 1960
	1960-78	Young 1982
Philippines	1850-1960	Baltazar 1964
Western Samoa	-1978	Western Samoa 1979

"Homoptera" is used for the Hemiptera *sensu lato* because of the large number of biological control introductions against homopterous pests.

Origin of pest. Here an opinion is given as to the original area of distribution of the pest before man began to spread pests to new areas. This may be the view of a specialist on the group or, in many instances, the compilers' own opinion based on distribution and origin of the host-plant or plants.

Crop. This field gives the crop, or crops, on which it was hoped to control the pest.

Table 2. Major reviews of biological control introductions against particular species of insect pests

Pest	Reference
COLEOPTERA	
Cosmopolites sordidus (Germar)	Waterhouse & Norris 1987
Epilachna spp.	Waterhouse & Norris 1987
Hypothenemus hampei (Ferrari)	Murphy & Moore 1990
Oryctes rhinoceros (L.)	Waterhouse & Norris 1987
DIPTERA	
Liriomyza spp.	Waterhouse & Norris 1987
HEMIPTERA	
Nezara viridula (L.)	Waterhouse & Norris 1987
HOMOPTERA	
Aleurodicus dispersus Russell	Waterhouse & Norris 1989
Aspidiotus destructor Signoret	Waterhouse & Norris 1987
Pseudaulacaspis pentagona (Targioni-Tozzetti)	Waterhouse & Norris 1987
Unaspis citri (Comstock)	Waterhouse & Norris 1987
LEPIDOPTERA	
Erionota thrax (L.)	Waterhouse & Norris 1989
Helicoverpa armigera (Hübner)	Waterhouse & Norris 1987
Lymantria dispar (L.)	Doane & McManus 1981
	Coulson *et al.* 1986
Opisina arenosella Walker	Cock & Perera 1987
Phthorimaea operculella (Zeller)	Sankaran & Girling 1980
Plutella xylostella (L.)	Talekar 1992
Spodoptera litura (F.)	Waterhouse & Norris 1987

Country. The name of the country, or island (regarded as separate introductions, particularly off-shore islands of mainland countries, e.g., Corsica, Hawaii, Sicily, Zanzibar, etc.) where releases were made is given, prefixed by a region in order to group countries with zoogeographical similarities. These regions approximate to those used by biogeographers, adjusted to country boundaries, and in some instances subdivided to provide convenient groupings (Figure 1).

Date. The dates entered are the year, or period of years, during which the agent was released. When new importations of the same agent were made from the same region the years when any additional releases were made are also indicated.

Agent. As for pest, the name of the parasitoid or predator is given, amended if necessary.

Classification of agent. Again the order and family of the agent are given in the same way as for the pest.

Origin of agent. Here the region, as for the origin of the pest, is given and, where indicated in the source, the country from which the agent was originally collected from the field and not the immediate source of the culture if it was obtained from an insectary in another country.

Result. The outcome of the introduction is indicated by a letter as follows:

F - failed to become established;
N - result not known;
E - permanently established;
T - temporarily established;
P - established and having some observed impact on pest numbers;
S - substantial control reported (i.e., other control measures not usually needed);
C - complete control (i.e., no other control measures required).

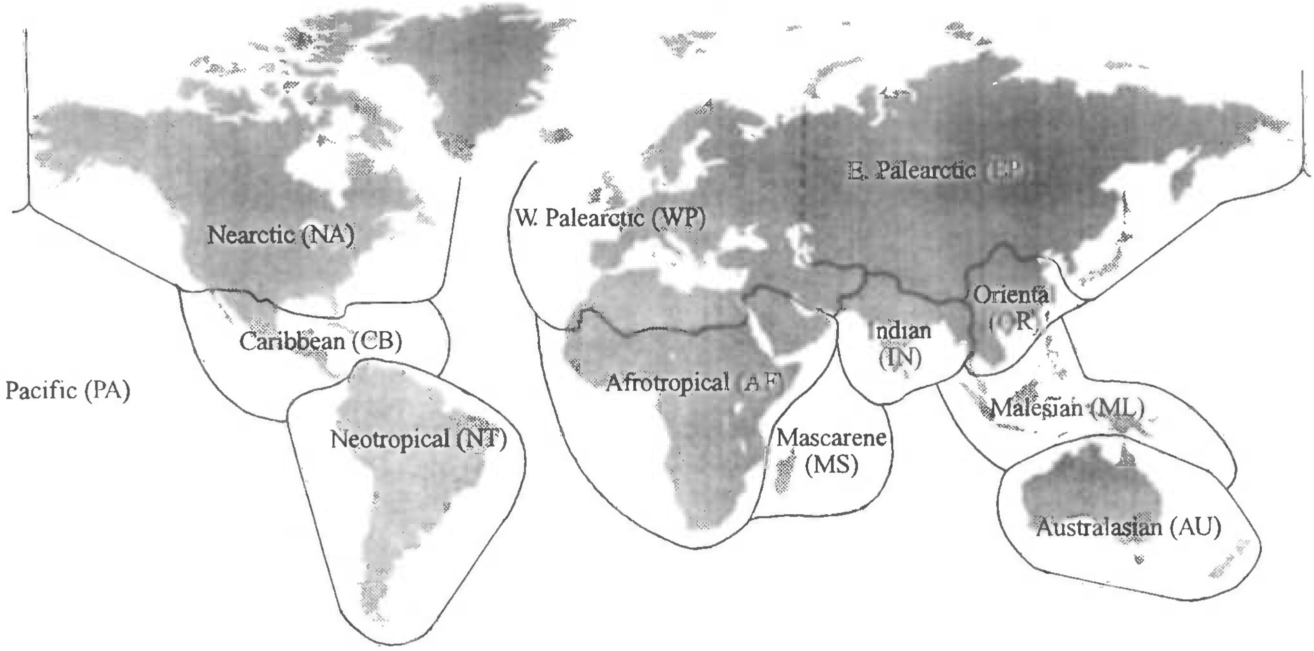

Fig. 1. Map showing regions used in BIOCAT (see text).

Where opinions differ, or a range is given in the source, more than one letter is used, e.g., S-C. In instances when control is credited to more than one introduced agent then an "&" is used and other records for the same pest and country should be checked.

Source. One reference is given, usually the most recent publication or sometimes the most authoritative statement of the outcome of the introduction. Where possible the reference chosen is a major review. References subsequent to the reviews were obtained by scanning the CAB ABSTRACTS database.

Note. An entry is included in this field if there is a comment on the record not appropriate for inclusion in the other fields.

When relevant information is not available this is indicated by a "-". A "?" is used when the sources are equivocal. Introductions have sometimes been made against categories of pests, e.g., "insects", "mealybugs", "stemborers", and such general terms are entered into the pest field when not even the genus of the pest is indicated in the source. However, the classification of pest field is filled as far as possible.

Records have been sorted to give a sequence listing records by the classification of the pest, the pest, country, classification of the agent and agent. Within these categories records are arranged alphabetically so that when scanning down similar pests appear in sequence and all records for a particular pest in the same country are together.

It is stressed that BIOCAT is based on published records as interpreted by the compilers and may not always reflect the true situation. Therefore, the records should be checked against the source documents, earlier reviews for the country (Table 1) or pest (Table 2), and other publications cited therein which may contain additional information. It will be found that opinions as to the outcome differ in a number of instances, hence where there are discrepancies the source considered to be the most authoritative is used. For example, the authors of the CIBC reviews were often able to consult departmental files and other unpublished documents not available to other reviewers relying on published information. Thus, these are cited in preference to Clausen (1978) for countries other than the continental USA. The Hawaii Department of Agriculture database (Lai and Funasaki, 1983 and summarized in Funasaki *et al.*, 1988) is cited for the Hawaiian islands.

INFERENCES FROM THE DATABASE

BIOCAT indicates that introductions have been made primarily to control some 543 species of pests. This has involved over 2000 species of parasitoids and predators in almost 200 different countries or islands (Table 3). It might be expected that inferences could be drawn from analysis of this considerable dataset. However, it is important to consider the defects of such databases which limit their predictive value. Thus, reporting of introductions is very uneven between countries, for example there are only summary data available for the former USSR and many Latin American countries, whereas the CIBC reviews give detailed accounts of projects and include unpublished information.

Understandably, researchers are more likely to publish their successes than their failures, so that it is probable that many failures remain unreported and estimates of success rates are likely to be too high. There is also a tendency for biological control practitioners to claim higher levels of control than other observers who have no personal interest in the outcome. Thus, it is often difficult from published accounts to be certain that biological controls are actually effective and that farmers are not using other control measures. For example, DeBach and Argyriou (1967) claimed successful control of citrus scale insects in Greece, but in 1975 the authors of this review (AHG and DJG) found that farmers did not agree and were carrying out routine spraying of their orchards.

Table 3. Summary of records included in BIOCAT

No. of introductions (total of records)	4769
No. of establishments (excluding F and N)	1445
No. of pests species	543
No. of agent species	2011
No. of countries and islands	196
No. of satisfactory controls (S and C)	517
No. of different pest species controlled	421

In many instances the outcome of introductions is not reported unless control is achieved, so that there are a large number of records in the unknown category which may be failures or have resulted in establishment without detectable impact on the abundance of the pest. There are, of course, also many recent introductions where the final outcome is not yet known. For all these reasons rating of results must be treated as unreliable without corroboratory evidence.

It needs to be borne in mind that biological control practitioners introduce the agents they believe are most likely to succeed and do not make introductions at random. Further, species that are successful on first introduction are more likely to be used again in other countries than those that failed. Similarly, certain families and genera are believed to contain more promising control agents than others, so that neither the species introduced nor the sequence of multiple introductions is unbiased. Therefore, inferences drawn by Ehler and Hall (1982) and others on the outcome of successive releases and the impact of previous introductions on successive introductions should be treated with caution.

All the same, if these limitations are kept in mind, some interesting inferences can be drawn from databases of biological control results.

Success Rate Over Time

Hall and Ehler's (1979) analysis of the records in Clausen (1978), which contains information published up to 1965, suggested that the establishment rate was declining in successive decades. Similar analysis of BIOCAT suggests that this trend has been reversed, and may be even more marked when recent results are fully published (Figure 2). The substantial decline in the number of introductions during the 1980s may, in part, be real, but is probably largely due to delays in publishing results. However, it is suggested that the decline in the number of new introductions, which began in the 1970s, and the rise in successful introductions is real and that the two are correlated.

During the 1950s and 1960s there was disillusionment with efforts to find a scientific basis for making introductions and many practitioners began to introduce all available natural enemies considered to have even the remotest chance of success with little care or detailed

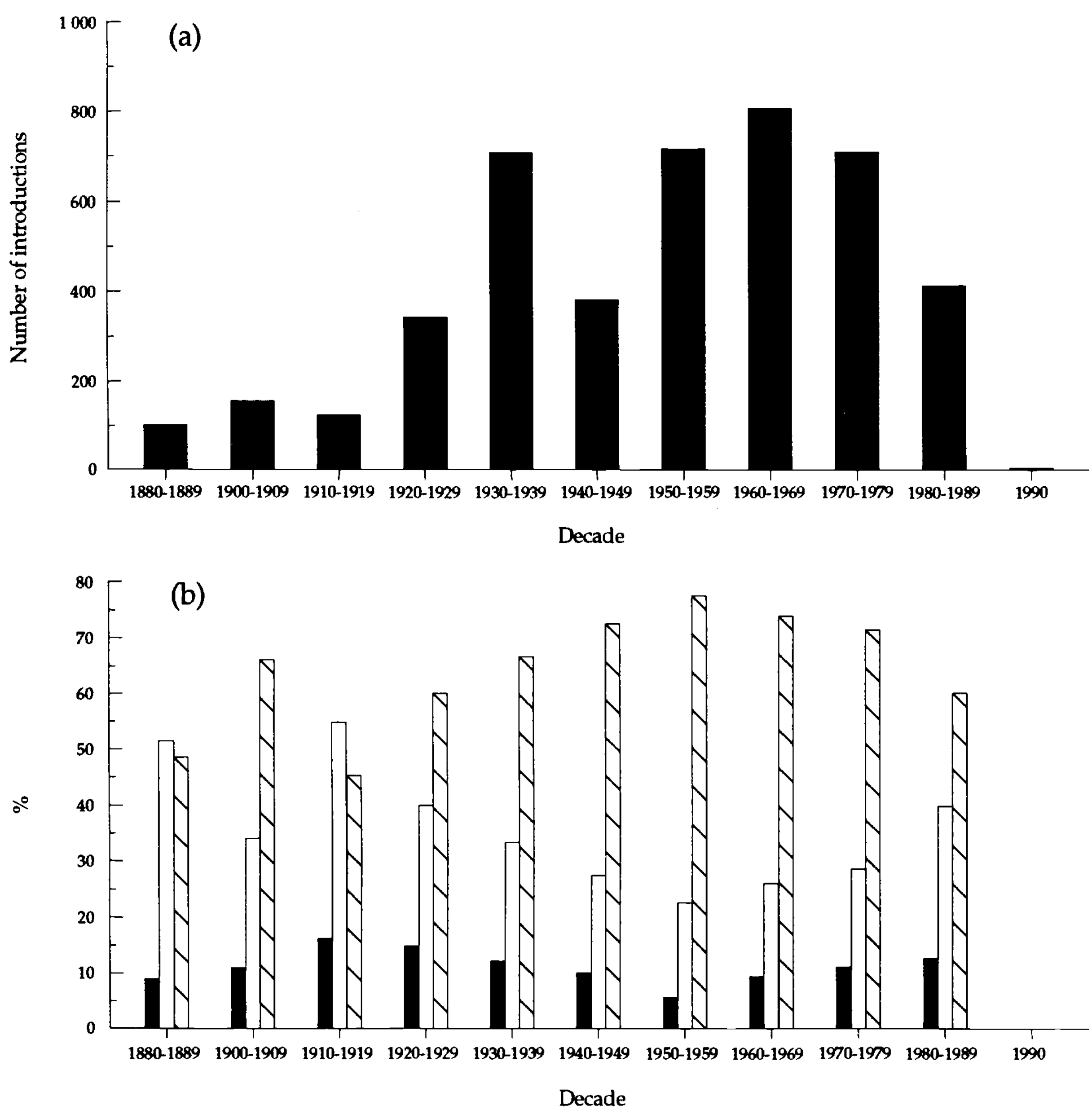

Fig. 2. a. Numbers of new introductions by decade. b. Percentage of introductions contributing to successes (black), establishments (white), and failures or unknown (hatched) by decade.

study of their host relations or ecological requirements. This approach was facilitated by the advent of rapid air transport, which made it possible for the first time to make introductions without the need for breeding the natural enemy, which was essential when natural enemies had to be transported long distances by sea. For example, parasitoids of pyralid stemborers from India and Indonesia, including those of the top borer *Scirpophaga nivella* (F.), *Chilo* spp., Neotropical *Diatraea* spp., and some from Africa primarily parasitizing noctuid borers, were exchanged between the Neotropics, Africa and Asia with remarkably little success (Figure 3).

Subsequent investigations showed that the parasitoids of *S. nivella* are unable to develop in *Diatraea* spp. (Bennett, 1965) and that some of the more important parasitoids of African noctuids show a strong preference for noctuid borers over pyralids (Mohyuddin, 1970, 1971, 1972). It was also found that details of the biology of some borers were important determinants of host range, e.g., *Chilo sacchariphagus* (Bojer) is unusual in pupating outside the stem and so is not a host for many pupal parasitoids, and certain borers, notably *Diatraea centrella* (Möschler) in the Caribbean, *C. sacchariphagus* in Indonesia and the Mascarene Islands and *Eldana saccharina* Walker in Africa, encapsulate many parasitoids capable of parasitizing most other species of pyralid borers.

Another important discovery was that one of the most promising parasitoids for borer control, *Cotesia flavipes* (Cameron), develops host and host-plant specific strains which can be manipulated in the laboratory to produce strains for particular combinations of host and host-plant (Mohyuddin, 1991). When this is done the success rate is increased. Now there is a tendency to make detailed ecological and life history studies before introductions are made, stimulated in part by the desire to increase the success rate so as to raise the reputation of biological control as an effective pest control technique and the increasing need to satisfy the authorities of the safety of proposed introductions. This increased care has reduced the number of species introduced against target pests and raised the success rate.

Another factor which has increased the rate of successful biological control in terms of the number of countries reporting successes is the rapid spread of a number of new pests in recent years, again a consequence of rapid air transport. Several of these new pests, e.g., cassava mealybug (*Phenacoccus manihoti* Matile-Ferrero) and mango mealybug (*Rastrococcus invadens* Williams) in Africa, woolly whitefly (*Aleurothrixus floccosus* (Maskell)) in the Americas and Europe, spiralling whitefly (*Aleurodicus dispersus* Russell) in the Pacific and a leafminer (*Liriomyza trifolii* (Burgess)), have proved excellent targets for biological control and have been the subjects of repeated successes by one or a few highly effective agents.

Host Systematics and Biological Control

The high proportion of Homoptera, particularly scale insects and mealybugs, which are the objects of successful biological control (Figure 4) has been noted many times (e.g., DeBach, 1964; Canada, 1971) and some of the reasons for this have been discussed in a preliminary analysis by Greathead (1989).

In contrast, many of the Lepidoptera, Hymenoptera and Coleoptera targetted for biological control have been native species which prove to be more difficult to control with exotic natural enemies, or have only invaded one or two countries, e.g., gypsy moth (*Lymantria dispar* (L.)) (60 introductions in the USA) and pine sawfly (*Neodiprion sertifer* (Geoffroy)) (10 introductions in Canada) in North America or the wood wasp (*Sirex noctilio* F.) in Australasia (12 introductions in Australia). Notable exceptions which have become widespread and have been the subject of massive effort are the diamondback moth (*Plutella xylostella* (L.)) on brassicas (84 introductions in 35 countries), the potato tuber moth (*Phthorimaea operculella* (Zeller)) (138 introductions in 21 countries), the coconut rhinoceros beetle (*Oryctes rhinoceros* (L.)) (87 introductions in 17 countries), and the Colorado potato beetle (*Leptinotarsa decemlineata* (Say)) (18 introductions in 9 countries).

However, the success rate for pests in these important holometabolous orders is lower than for Homoptera, but important successes have been obtained and repeated, e.g., diamondback moth (8 successful controls) and potato tuber moth (7 successful controls).

There have also been notable failures, for example a chafer beetle (*Phyllophaga smithi* (Arrow)), which occurs naturally only in Barbados, was inadvertently introduced into Mauritius before 1911 and 36 introductions of parasitoids of Scarabaeidae were made from all over the world during 1913–1949, resulting in the establishment of only four species of scoliids which had an equivocal impact (Greathead, 1971). Similarly the campaign to control the gypsy moth in North America, which began

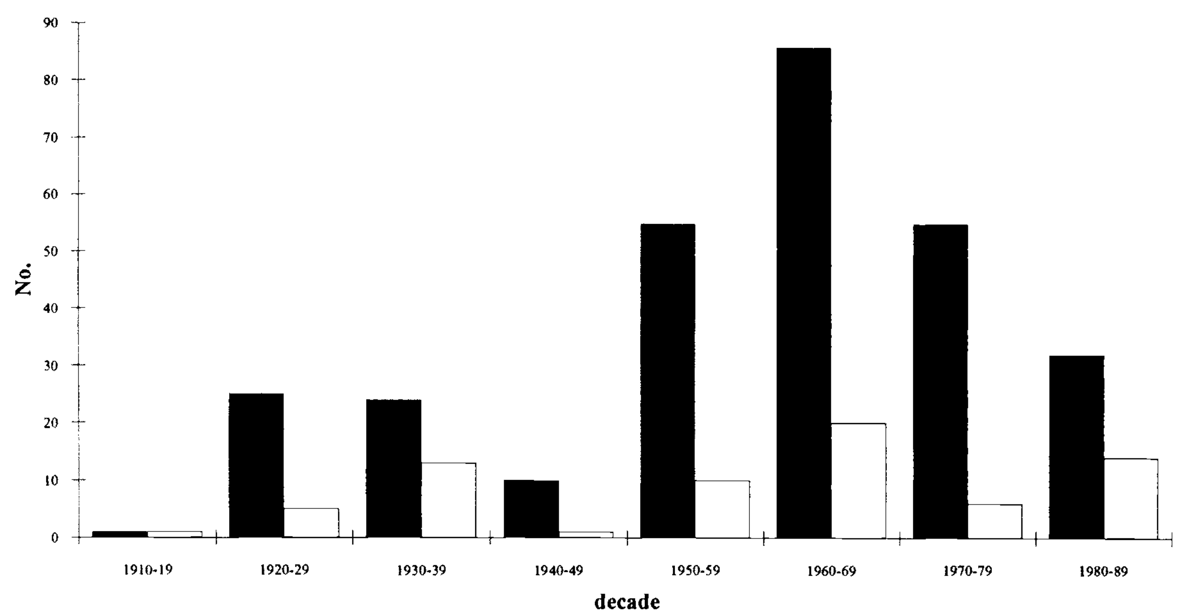

Fig. 3. New introductions against tropical cereal stemborers by decade. Total introductions (black), establishments (white).

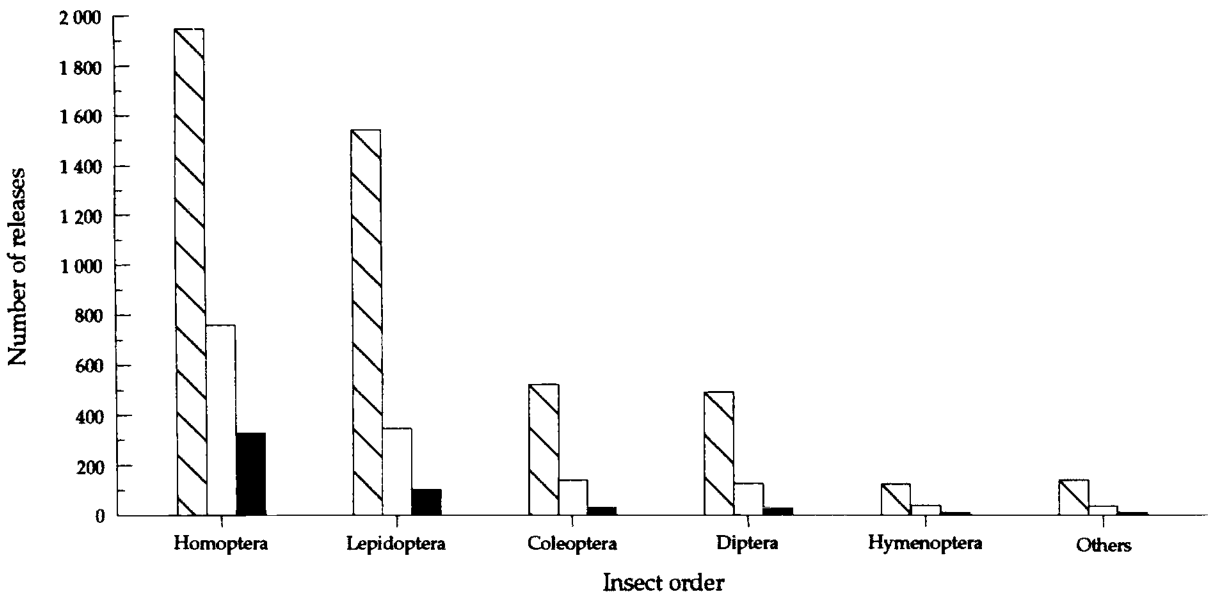

Fig. 4. Numbers of new introductions by order of pest. Total introductions (hatched), establishments (white), contributing to successful controls (black).

in 1906, still continues after 60 introductions. Other unsuccessful programmes include the attempts to control the Colorado potato beetle in Europe.

Agents Used for Biological Control

As expected, Hymenoptera have been by far the most used order of entomophagous insects to be introduced as biological control agents (Table 4). Greathead (1986) analysed the family and generic composition of these introductions using an earlier version of BIOCAT. Introductions of the Diptera are dominated by the Tachinidae, the only large and important family of parasitoids, and the Coleoptera by the Coccinellidae, the most used family of predatory insects. The remaining orders containing parasitoids and predators make a negligible contribution to the total, i.e., the Neuroptera, Hemiptera, Dictyoptera, Thysanoptera, Lepidoptera, Odonata.

Geographical Distribution of Effort

The distribution of biological control effort between countries (and islands) is very uneven. Thus, the 10 countries (Table 5) which have made the largest contribution account for 45% of the total number of introductions and 39.5% of introductions leading to successful controls; nine of them have made over 100 introductions. Most of these countries began using biological control and achieved an early success, most of them before 1920. As noted by Greathead (1992), once a country has achieved one successful biological control programme it is likely to continue to consider biological control when new pest problems arise. In this respect the recent successes in Africa against the cassava mealybug and mango mealybug have alerted many countries which had not previously attempted biological control to the value of this method of pest suppression.

Islands v. Continents

It is noteworthy that the list of the top ten countries includes six groups of islands, because it has frequently been argued that islands are more suited to successful biological control than continental areas. However, Greathead (1971) could find no evidence to support this hypothesis in relation to Africa and its associated islands and others, notably Hall and Ehler (1979) and Hall *et al.* (1980) were also unable to find evidence in support. However, these authors did detect a higher rate of establishment on islands, which Greathead (1971) suggested is due to their depauperate fauna and consequently invading species have a greater chance of successful colonization than in species rich continental areas. The data in Table 5 tend to support the conclusion that the success rate is not greater on islands, but not the hypothesis that establishment is easier on islands.

However, comparisons should be between island and continental areas with a similar climate and biota.

Table 4. Principal agents used in biological control introductions

Order	No. of introductions	No. of species	No. of successes	No. of successful species
Coleoptera	1023	419	88	14
Coccinellidae	783	285		
Diptera	437	218	37	9
Tachinidae	343	159		
Hymenoptera	3210	1317	384	97
Braconidae	798	272		
Aphelinidae	466	136		
Encyrtidae	451	184		
Ichneumonidae	381	206		
Eulophidae	274	121		

Table 5. Countries making the largest number of introductions

Country	No. of introductions	No. of successes	No. of establishments
USA	722	63	237
Hawaii	564	49	195
Canada	224	14	56
New Zealand	184	16	54
Australia	161	16	61
Bermuda	153	11	27
Fiji	133	10	34
Mauritius	129	15	33
Mariana Is	122	16	45
India	92	4	28

Moreover, the data for two of the top ten is influenced by large and unsuccessful programmes: 50 introductions were made against Bermuda cedar scales in Bermuda, from which only three species became established, and 37 against *Phyllophaga smithi* in Mauritius, of which only six were established. Further, the impressive score for the Mariana Islands is possibly due to the small number of new programmes initiated there; the majority of introductions are of species that were previously successful in Hawaii.

CONCLUSION

BIOCAT and similar databases provide a useful summary of biological control effort and a guide to factors which may influence the chances of success in these and future programmes, but the information is not of sufficient quality or reliability to make firm predictions. For this purpose much more detailed information is required and analyses should be confined to smaller categories of data, so that like can be compared with like and differences are not confounded by the inclusion of data from disparate regions or of organisms with markedly different ecological requirements.

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