IOBC Internet Book of Biological Control, version 6

Editor: J.C. van Lenteren (Joop.vanLenteren@wur.nl)

Aim: to present the history, the current state of affairs and the future of biological control in order to show that this control method is sound, safe and sustainable

Contents

NEW IN VERSION 6:

- New Chapter: Evaluation and ranking of new natural enemies
- New Chapter: Benefits and costs of biological control
- New Chapter: Environmental risks and risk assessment of natural enemies
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- Appendix 2: Glossary of terms related to biological control
- Appendix 3: Guidelines for the export, shipment, import and release of biological control agents (ISPM 3, 2005)
- Appendix 4: EPPO standard on import and release of natural enemies
- Appendix 5: White list of natural enemies
- Additions to Chapter 3 and 4
- Aditions to Appendix 1: overview of national and regional biological control books

Invitation

Please provide us with material on any of the topics mentioned above. Your assistance is crucial to obtain a reliable, worldwide picture of the importance of biological control. You can either send material per email to the editor, or by post to Prof.dr. J.C. van Lenteren,

Laboratory of Entomology, Wageningen University, P.O. Box 8031, 6700 EH, Wageningen, The Netherlands.

Warning and Request:

1. The first versions of this internet book are strongly biased, so provide me with better/other information and the result will be a more balanced version
2. If you find mistakes or better data than given below, contact me!
3. You are free to use the information presented in this internet book, but be so kind to refer to this source as: J.C. van Lenteren (ed.), 2007. Internet Book of Biological Control. 4th Edition, www.IOBC-Global.org, Wageningen, The Netherlands.

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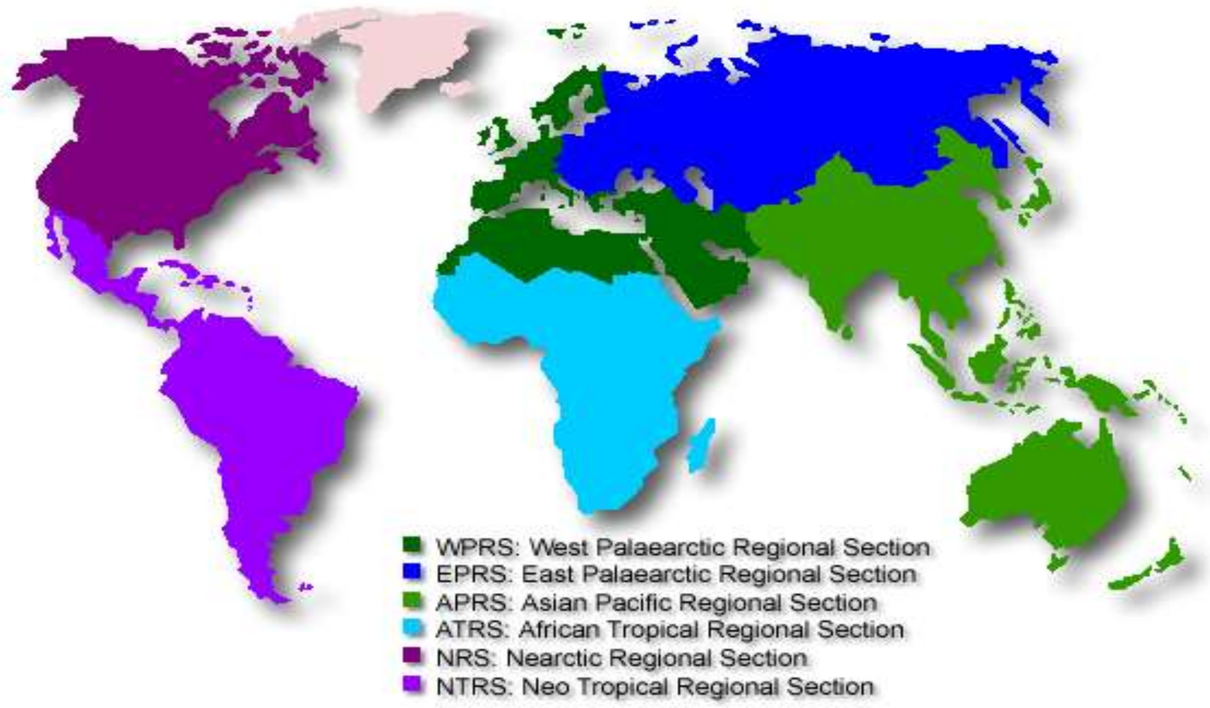
Aim of the International Organization for Biological Control of Noxious Animals and Plants (IOBC-Global) is to promote the development of biological control and its application in integrated control programmes.

IOBC coordinates biological control activities worldwide and has 6 regional sections (Africa, Asia, East Europe, North America, South America, and West Europe) and many working groups.

The mission of IOBC Global is illustrated in the following mission statement: “Biological control is a science-based process, planned, conducted, delivered and evaluated by teams of colleagues. There is a high degree of international cooperation and free exchange of biological control germplasm. The highest ethical and scientific standards are upheld in the conduct of biological control. It is investigated as the first option for pest management, and replaces chemical control as the base strategy of integrated pest management. The desired outcome of biological control is science-based, sustainable, cost-effective, resource-conserving and environmentally compatible management of pests of agriculture, forestry, medical and veterinary importance, urban areas, interiorscapes and environmental areas. Biological control results in a global reduction in pesticide use and conservation of biological diversity.”

Boller, E.F, J.C. van Lenteren and V. Delucchi (eds.) 2006. International Organization for Biological Control of Noxious Animals and Plants: History of the first 50 Years (1956-2006). IOBC, Zürich, 287 pp. This book can be obtained by sending 10 Euro or 15 US Dollars in an enveloppe to Prof.dr. J.C. van Lenteren, Laboratory of Entomology, Wageningen University, POBox 8031, 6700 EH, Wageningen, The Netherlands.

For all information about IOBC and it's regions, go to www.IOBC-Global.org



International role and accomplishments of IOBC

IOBC is the only truly worldwide organization representing research in biological control in various global, regional and national organizations (e.g. IUBS, FAO, EC, ICE) for more than 50 years

IOBC developed practically applied biological control and integrated pest management programs

IOBC was the first to develop IPM guidelines for all major crops in Europe and has since continued to contribute to the development of principles of sustainable agriculture, e.g. guidelines on Integrated Production.

IOBC initiated and co-developed Guidelines for the export, shipment, import and release of biological control agents and other beneficial organisms (International Standard for Phytosanitary Measures Number 3, 32 pages, 2005; Secretariat of the International Plant Protection Convention; available at www.FAO.org)

IOBC initiated and co-developed methods to test side effects of pesticides on natural enemies, which are now the official standard for testing side effects in the European Union pesticide registration procedure and published as the EPPO standard for Environmental Risk Assessment Scheme for Plant Protection Products, Chapter 9, PP 3/9, EPPO Bulletin 33, 99-131; available at http://archives.eppo.org/EPPOStandards/PP3_ERA/pp3-09(2).pdf).

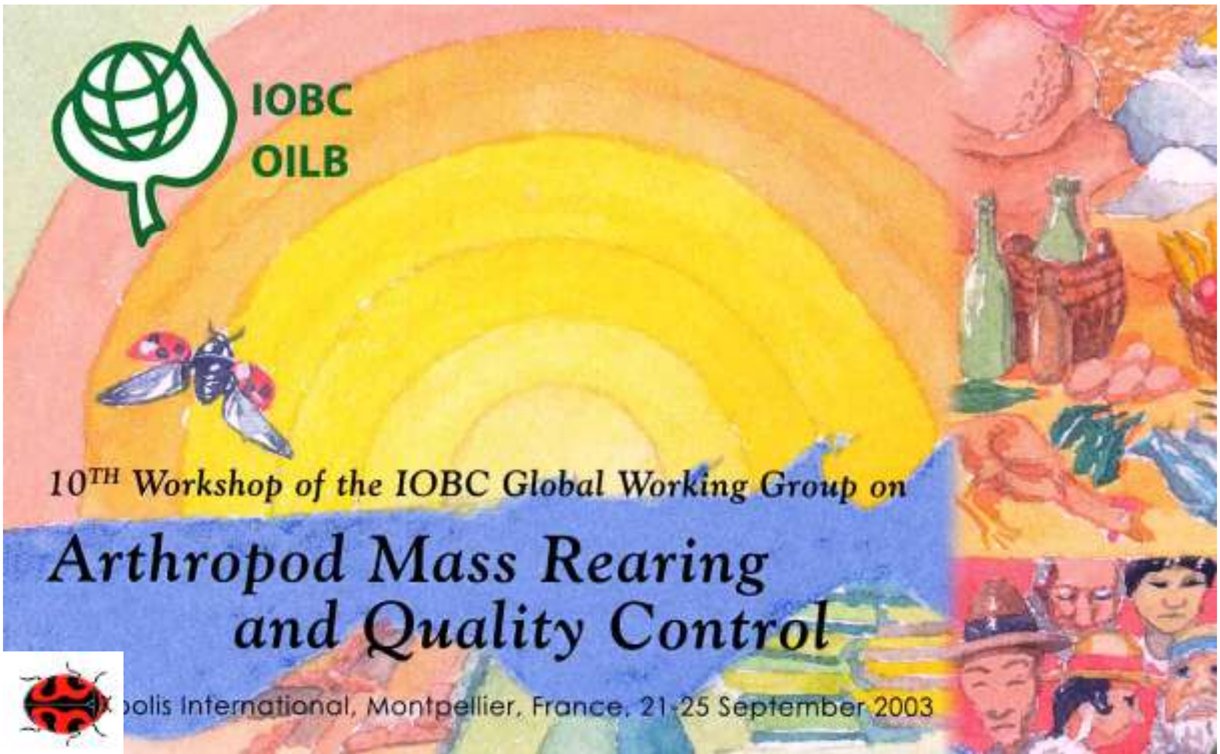
IOBC initiated and co-developed with the natural enemy producers guidelines for mass production and quality control of beneficial organisms (see: http://www.amrqc.org)

IOBC co-developed with OECD a document on Guidance for Information Requirements for Regulation of Invertebrates as Biological Control Agents (IBCAs) (OECD Series on Pesticides Number 21, Environment Directorate; Organisation for Economic Co-Operation and Development, Paris 2003, 22 pages; Available at http://www.oecd.org/dataoecd/6/20/28725175.pdf)

IOBC contributed information on biological control and biodiversity to the FAO report "Genetic resources of importance to agriculture" (to appear in 2007)

Reviewed and made important contributions to paragraphs on sustainable agriculture and pest management in the UN-coordinated International Assessment of Agricultural Science and Technology for Development (to appear in 2008)

Provided information to several organizations about natural enemies as quality indicators for biodiversity, and natural enemies as test organisms for side effects of pollutants and for pesticides as indicator of in and off field non-target effects



Stamp related to the success of biological control research in The Netherlands, showing greenhouse whitefly and *Encarsia formosa*

1. Introduction

Biological control* - the use of an organism to reduce the population density of another organism - is the most successful, most cost effective and environmentally safest way of pest** management. It is nature's own way to keep numbers of pest organisms at low levels. Biological control is present in all ecosystems, both natural and man made, and is always active. The result of natural biological control is that the earth is green and that plants can produce sufficient biomass to sustain other forms of life. Without biological control, the production of energy by plants would be a tiny fraction of what is produced currently.

Natural (biological) control is the reduction of pest organisms that occurs "for free" since the evolution of the first ecosystem some 500 million years ago, can be found in all ecosystems and takes place without human interventions. In addition to natural forms of biological control, man started to use arthropod biological control around the year 300 by using predatory ants for control of pests in citrus orchards (see: first use of predators).

Large scale use of biological control started in 1888 with the release of *Rodolia* ladybird beetles to control a scale insect in citrus in California (see below). Many permanent successes have been obtained since, resulting in annual profits of millions of dollars, and these profits are accumulating continuously as biological control is permanent in contrast with chemical control where resistance against the pesticide develops.

Due to the facts that (1) earth will have to feed about 11 billion human beings in the near future, (2) fossil energy is running out, and thus are conventional synthetic pesticides, (3) man cannot continue to pollute the environment and reduce biodiversity at the same dramatic rate as during the past 100 years, agricultural research needs to be redirected to a systems approach. In such an approach, pest management will be a guiding theme instead of being the marginal issue it was during the past 60 years. Guiding, because methods to prevent or reduce pests influence all agronomic methods from the design of cropping systems to the harvest of crops. Modern pest management will strongly depend on biological control, because it is the most sustainable, cheapest and environmentally safest pest management method (see table 1) In additon, it has important benefits for farmers and consumers (see table 2). Biological control is expected to make up 35-40% of all crop protection methods in the year 2050.

*Biological has been defined in many ways. The simplest definition is: using biota to reduce biota (International Biological Program)

**Pest = organism (plant, animal or protist) occurring in such numbers that it creates damage

Biological control at work: no problem to enter the greenhouse and harvest the crop at the optimal moment! With chemical control, there is generally a no-entry period of several days to protect workers from health risks

Some facts about biological control:

- Natural (biological) control is constantly active in all world terrestrial ecosystems on 89.5 million km^2
- Most of the potential arthropod pests (95%, 100,000 arthropod species) are under natural (biological) control; all other control methods used today are targeted at the remaining 5,000 arthropod pest species. This ecosystem function of natural biological control is estimated to have an annual minimum value of 400 billion US$ per year (Costanza et al., 1997), which is an enormous amount compared to the only 8.5 billion US$ annually spent on insecticides.
- Classical biological control is applied on 3.5 million km^2 (350 million hectares), which is about 8% of land under culture, and has very high benefit-cost ratios of 20-500 : 1
- Augmentative, commercial biological control is applied on 0.16 million km^2, which is 0.4 % of land under culture, and has a benefit-cost ratio of 2-5 : 1, which is similar to or better than chemical pest control
- More than 5,000 introductions of about 2,000 species of exotic arthropod agents for control of arthropod pests in 196 countries or islands have been made during the past 120 years, and more than 150 species of natural enemies (parasitoids, predators and pathogens) are currrently commercially available (van Lenteren et al., 2006).

Table 1. Comparison of data on performance of chemical and biological control (after Lenteren, J.C. van, 1997. From *Homo economicus* to *Homo ecologicus*: towards environmentally safe pest control. In: Modern Agriculture and the Environment, D. Rosen, E. Tel-Or, Y. Hadar, Y. Chen, eds., Kluwer Acadamic Publishers, Dordrecht: 17-31.)

	Chemical control*	Biological control
Number of ingredients tested	> 3,5 million	2,000
Success ratio	1 : 200,000	1 : 10
Developmental costs	150 million US$	2 million US$
Developmental time	10 years	10 years
Benefit / cost ratio	2 : 1	20 : 1
Risks of resistance	large	small
Specificity	very small	very large
Harmful side-effects	many	nil/few

*Data for chemical control originate from material provided by the pesticide industry; data as per 2005. In 1980 10,000 compounds were tested per year, in 2004 this had increased to 500,000 per year (Stenzel, 2004)

Thousands of natural enemy species have not yet been tested for usefulness in biological control programs

Table 2. Advantages of biological control for farmers and consumers

Why do farmers use biological control? They mention the following advantages (e.g. van Lenteren, 2000):

1. Strongly reduced exposure of grower and spray personnel to toxic pesticides
2. Lack of residues on the marketed product
3. Lack of phytotoxic effects on (young) plants, and no premature abortion of flowers and fruit. As a result, often yield increases are obtained when biological control is applied.
4. Release of natural enemies takes less time and is much more pleasant than applying chemicals in humid and warm greenhouses
5. Release of natural enemies usually occurs shortly after the planting period when the grower has sufficient time to check for successful development of natural enemies; thereafter the system is reliable for months with only occasional checks; chemical control requires continuous attention,
6. Chemical control of some important agricultural pests is difficult or impossible because of pesticide resistance
7. With biological control there is no safety period between application and harvesting the crop, so harvesting can be done at any moment which is particularly important with strongly fluctuating market prices; with chemical control one has to wait several days before harvesting is allowed again
8. Biological control is permanent: once a good natural enemy - always a good natural enemy
9. Biological control is appreciated by the general public. This may result in either a quicker sale of crops produced under biological control, to a better price for these crops, or both.

Consumers, politicians and policy makers add the following important advantages this list of the growers:

1. Low risk of food, water and environmental pollution
2. Contribution to sustainable food production
3. Contribution to protection or even improvement of biodiversity
4. No pesticide residues on food

Table 3. Estimated world market value natural and commercial biological control and biologically based pest management

Control method	US$ billions
Natural biological control[1]	400,000 x 10^6
Biological control with arthropods and nematodes[2]	,130 x 10^6
Biological control with micro-organisms[2]	,020 x 10^6
Bacterial and fungal-derived toxins[2]	,120 x 10^6
Botanical pesticides[2]	,100 x 10^6
Behavioural modifying chemcicals[2]	,070 x 10^6
Plant material resistant to pests and diseases, non GMO[2]	6,000 x 10^6
Plant material resistant to pests, diseases and herbicides, GMO	PM

[1]Costanza et al., 1997. [2]extrapolated from van Lenteren, 1997, various recent unpublished sources and Bolckmans/Ravensberg personal communication November 2005

Table 4. Estimated world market for chemical pesticides in 2004 (Agrow 466, 18 February 2005)

Pesticide	US$ billions	%	Euro billions
Herbicides	14,829x 10^6	45.4	12,161 x 10^6
Insecticides/Acaricides	8,984 x 10^6	27.5	7,366 x 10^6
Fungicides	7,088 x 10^6	21.7	5,812 x 10^6
Others	1,764 x 10^6	5.4	1,446 x 10^6
Total	32,665 x 10^6		26,785 x 10^6

References

Costanza et al., 1997. The value of the world's ecosystem services and natural capital. Nature 387: 253-260.

Lenteren, J.C. van, 1997. Biologically-based crop protection: major trends for the 21st Century. In: Plant Based Specialty Products and Biopolymers, L. Andreasen, ed. Nordic Council of Ministers, Copenhagen, Report NKJ-seminar, 1996: 121-135.

Lenteren, J.C. van, 2000. A greenhouse without pesticides: fact of fantasy? Crop Protection 19:375-384.

Lenteren, J.C. van, Bale, J., Bigler, F, Hokkanen, H.M.T., Loomans, A.J.M., 2006. Assessing risks of releasing exotic biological control agents of arthropod pests. Annual Review of Entomology, 51: 609-634.

Stenzel, K., 2004. From genes to compound discovery: unique research platform combining innovative screening technologies. Pflanzenschutz-Nachrichten Bayer 57-2004, 35-45.

2. Discovery of natural enemies and a bit of entomological history

Origin of entomology and ecology (after Needham, 1956 and Smith et al., 1973; for full text see van Lenteren, 2005)
Current opinion is that entomology originated in China. The Chinese have invented sericulture in 4700 BC, the culture of mulberry plants and the indoor rearing of silkworms in 1200 BC, chemical control of insects in 200 AD, biological control of insects with predatory ants and insect ecology in 300 AD, honey bee rearing in 400 AD, etc. etc. (Chou, 1957; Konishi and Ito, 1973). The idea of the food web was first recorded in China in the third century: A factor which increases the abundance of a certain bird will indirectly benefit a population of aphids because of the thinning which it will have on the coccinellid beetles which eat the aphids but are themselves eaten by the bird (Needham, 1956)." These two examples concern the role of three species of predators in biological pest control, a bird, a coccinellid and an ant. In fact, they are also early descriptions of what we would characterize in modern ecology as studies on multi-trophic interactions.

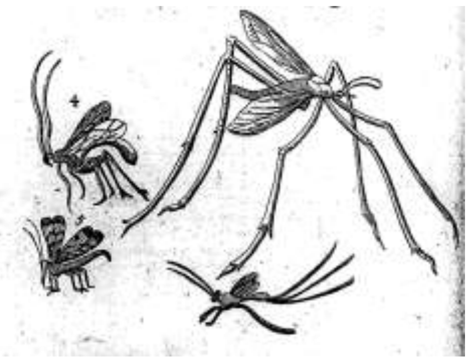
See the table at the end of this chapter for an overview of important historical facts in the history of entomology

History of entomology in Europe (after Beier, 1973 and Morge, 1973; for full text see van Lenteren, 2005)
In Europe, Aristotle (384-322 BC) is usually seen as the founder of general entomology and of entomology as a science (Morge, 1973), although other Greeks, starting with the poet Homer (ca. 850 BC), wrote about insects. Aristotle classified insects, and had a good knowledge of anatomy and morphology. It is worth mentioning here that Aristotle in his *Historiae animalium* describes the attack by hymenopterans on spiders as follows: "The wasps called "ichneumon", which are smaller than other wasps, kill spiders, carry them in some crevice of a wall or somewhere else, knead them with mud, and lay into them their eggs from which other ichneumon wasps are generated".

During Roman antiquity, there was little interest in pure entomology, with the exception of Pliny (23-79; Gaius Pliny Secundus, or Pliny Maior) but he scarcely made any original observations in nature. The Romans did, however, write major works on agricultural entomology in the period from 250 BC until 400 AD, which contain many suggestions for pest prevention or control (Morge, 1973).We have to wait till the end of the 12th century for new developments, when Europe was re-acquainted with the heritage of the Greeks and Romans, revived by the Arabs in the preceding centuries. Based on the translation of Arabian sources by the Scotsman Michael Scotus, much of the lost knowledge was regained (Morge, 1973). A great work of the later Middle Ages relating to entomology is the *Ruralium Commodorum Libri XII* written between 1304 and 1309 by the Italian Pier De' Crescenzi (1230 - ??). He added his own observations to earlier collected material. His book became the European manual of agriculture for about 300 years and contained many measures to prevent or control insect pests (Morge, 1973).

During the next three hundred years, very few developments in entomology occurred in Europe due to the prevalent mysticism and all-controlling doctrinal dogma of the church (Beier, 1973). Even the discovery of the printing press (approximately 1450) could initially not help to spread entomological information to further educate people. Some books appeared with illustrations of insects, but the poor quality of the wood engravings made them unrecognizable. During this period, the works of

Aristotle and Pliny were translated again, and once more without adding new information. Due to an increasing amount of misunderstandings, errors, mistakes and misinterpretations, these translations led to an even vaguer image of entomology than before. It took until the appearance of *De Differentiis Animalium Libri Decem* in 1552, written by the Englishman Edward Wotton (1492-1555), before a good summary became available of knowledge accumulated before, including the work of Aristotle. In this same period, Conrad Gessner (1516 - 1565), wrote his *Historia animalum*, including one volume on insects (published posthumously in 1634; for details, see Vidal, 2005). Gessner, like Wotton, also compiled earlier knowledge, but included his own observations. Most of the other publications from this period in which insects are mentioned were still strongly influenced by mysticism, absurdism, and moralism related to religion.



A real breakthrough in entomology was the work of the Italian Ulisse Aldrovandi (1522-1605). Although he was still much subjected to the influence of Aristotle, he was an excellent observer and exposed facts that he had determined by his own research. As a pioneer of pure natural research, he was by far the most outstanding among the compilers of his time. He produced several hundred volumes of manuscripts and excerpts. His big folio-volume *De Animalibus Insectis libri VII*, published in 1602, was the first work of literature in the world dealing with insects and illustrated with recognizable wood engravings. He thus finally established entomology, and especially systematic entomology as a science (Beier, 1973). He was also the first to describe the emergence of parasitoid larvae from a host caterpillar (see Tremblay and Masutti, 2005). His interpretation of the emergence of larvae was, however, not yet correct and it would take about another 60 years before the first accurate interpretations of insect parasitism appeared in Europe.

To be added: history of entomology in other regions; please provide us with material

Discovery of predators (after Smith et al., 1973; for full text see van Lenteren, 2005)

Because of the obvious act of predation, predators have been mentioned for pest control long

SCIENCE AND CIVILISATION IN CHINA

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VOLUME 6

BIOLOGY AND BIOLOGICAL TECHNOLOGY

PART I: BOTANY

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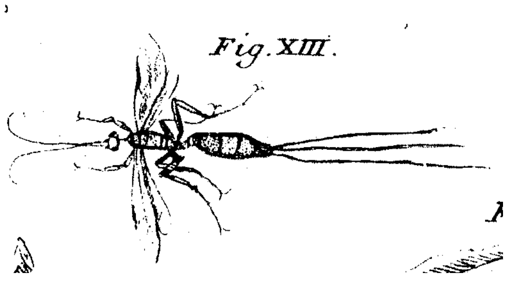
ago in many independent sources (see e.g. Needham, 1956, 1986; and various authors in Smith et al., 1973). Early farmers might have already observed and appreciated the action of predators, as predation is obvious and easy to understand. Biological control was first applied when man began keeping cats to protect stored grain from damage by rodents. The earliest recorded historical example of biological control concerns Egyption records of 4,000 years ago that depict domestic cats as useful in rodent control. Thus, predators like cats were already used for thousands of years to control mice. Konishi and Ito (1973) state that “The Chinese were the first to use natural enemies to control insect pests. Nests of an ant, *Oecophylla smaragdina*, were sold near Canton in the third century to use for control of citrus pests such as *Tesseratoma papillossa* (Chi Han, approximately 300 AD: Nan Fang Tshao Mu Chuang: Records of the Plants and Trees of the Southern Regions). The ants build nests in trees and such nests were collected and sold to

farmers. In order to aid the foraging of the ants, bamboo bridges were build between the citrus trees. DeBach (1974) observed this practice still being used in North Birma in the 1950s and Needham (1956) mentions of its continued use in China. All early efforts employed general predators like mongooses, owls an other birds, toads, ants and the like. The earliest graphic record of an insect also concerns a predator, the hornet *Vespa orientalis*, which was depicted as an hieroglyph representing the Kingdom of Lower Egypt by King Menes about 3100 BC (Harpez, 1973). It can still be seen today on wall paintings and inscriptions in pillars in many of the ancient temples and tombs in the Nile Valley.

Discovery of parasitoids (for full text see van Lenteren, 2005)
Insect parasitism was understood much later than the phenomenon of predation, because of the complicated biological relationships between parasitoids and their hosts. Although often described as parasites, "entomophagous insects" are not strictly parasites: they are parasitoids (Reuter, 1913). True parasites live at the expense of their hosts without actually causing the death of the host. Parasitoids always kill their host, after spending the larval period as a true parasite; the adult is free-living. Despite this distinction, the term 'parasitic wasps' is still widely used.

After the first use of insect predators in approximately 300 AD in China, it would take about 800 years in China and almost 1300 years in Europe before the phenomenon of insect parasitism was discovered. As a result of the study of old publications reported in papers by Cai et al. (2005), the discovery of insect parasitoids by the Chinese can now be put at 1096, which is about 600 years earlier than was thought until October 2000. Insect parasitism was known in China for a long time in the form of parasitic tachinid flies of silkworms (*Bombyx mori* L.). These tachinid flies were first mentioned in Chinese literature around 300 A.D. The developmental cycle of this tachinid (possibly a species of the genus *Exorista*), including egg deposition on the host, were clearly described by Lu Dian in 1096. This antedates the first descriptions of insect parasitoids from Europe with about 600 years. Another parasitic fly, a flesh fly (possibly *Blaesoxipha lapidosa* Pape) was noted as the main parasitoid of *Locusta migratoria manilensis* Meyen in 1196. The first Chinese record with a correct description of the life cycle of a hymenopteran parasitoid dates from 1704.

Early European literature had apparently been poorly studied until recently, because many new facts about insect parasitism were found in this literature, and the European discovery of parasitism can be predated with 25 years (van Lenteren & Godfray, 2005). The authors most frequently credited for the European discovery of the parasitoid life cycle are Antoni van Leeuwenhoek, John Ray and Antonio Vallisnieri around the year 1700. Other authors who published works on entomology in the 17th century, and who mentioned insects that we now recognize as parasitoids, were supposed until recently not to have understood the parasitoid life cycle. After rereading much of this literature, this supposition appears to be correct for Aldrovandi, Goedaert, Johnston, Malpighi, Mouffet and Redi (van Lenteren & Godfray, 2005). However, Lister, Merian and Swammerdam (with the help of the painter Marsilius) all arrived at the correct interpretation of insect parasitism after observing most or all life



history stages. The first correct interpretation of parasitism that we can trace, but which does not include the critical observation of oviposition by the adult female, is that of Swammerdam in 1669. The first recorded observation of oviposition that we can find is by the painter Marsilius but described by Swammerdam in 1678. Van Lenteren and Godfray (2005) thus suggest Jan Jacob Swammerdam (assisted by Otto Marsilius) should be credited with the description of the discovery of the parasitoid life cycle in Europe.

For the discovery of parasitism in Germany, Italy, France and Japan, see repectively Vidal (2005), Tremblay & Masutti (2005), Carton (2005) and Hirose (2005).

Discovery of insect parasitism in Africa, North, Central and South America, Asia (except China), Australia and New Zealand took place after 1700 (for references, see van Lenteren, 2005). We appreciate receiving information about the discovery of insect parasitoids and predators for other countries.

The discovery of insect parasitism in the 11th century in China and in 17th century in Europe, has led to the highly successful and environmentally safe use of hundreds of species of parasitoids in biological control today (e.g. Gurr and Wratten, 2000; van Lenteren, 2003; van Lenteren et al., 2006).

See table 1 below for an overview of important historical facts in the history of entomology.

Table 1. Highlights in entomology and discovery of parasitoids (for full text, see van Lenteren & Godfray, 2005)

ca - 310	Aristoteles (Greece, 384 - 322 BC) *Historia Animalum*, natural history and taxonomy of animals
ca 300	Guo Pu (China, 276 - 324) *Commentary on the Literary Expositor*, mentions tachinid parasitoid but does not understand its biology (see Cai et al., 2005)
1096	Lu Dian (China, 1042 - 1102) *New Additions to the Literaty Expositor*, observes and describes the full cycle of insect parasitism by tachanid parasitoid; **first description of phenomenon of insect parasitism based on observation of complete life cycle** (see Cai et al., 2005)
1321	Dante Alighieri (Italy, 1265 - 1321) *La Divina Commedia*, many records to insects
1551-1634	Conrad Gessner (Germany, 1516 - 1565) *Historia Animalum*, encyclopedic work summarizing all earlier information and his own obervations, classification of animals, the volume on insects was published posthumously in 1634 (see Vidal, 2005)
1552	Edward Wotton (Britain, 1492 - 1555) *De Differentiis Animalium Libri Decem*, encyclopedic work summarizing earlier information
1602	Ulisse Aldrovandi (Italy1522 - 1605) *De Animalibus Insectis Libri VII*, observed emergence of parasitoid larvae from caterpillar, did not understand phenomenon; Aldovrandri's book is considered the first work in pure entomology (see Tremblay and Masutti, 2005)
1660	John Ray (Britain, 1627 - 1705) *Catalogus Plantarum circa Cantabrigiam nascentium*, observes emergene of parasitoid larvae from caterpillar in 1658 (see van Lenteren and Godfray, 2005)
1662	Johannes Goedaert (Holland, 1617-1668) *Metamorphosis Naturalis*, 3 volumes with many drawings of larvae, pupae and adults of parasitoids, describes emergence of larvae and adults of parasitoids, does not understand phenomenon of parasitism (see van Lenteren and Godfray, 2005)
1668	Francesco Redi (Italy, 1626 - 1697) *Esperienze Intorno alla Generazione degli Insetti*, observation of emergence of parasitoid larvae from host, but did not understand phenomenon of parasitism (see Tremblay and Masutti, 2005)
1669	Jan Swammerdam (Holland, 1637 - 1680) *Historia Insectorum Generalis*, observed many parasitoids in larval, pupal and adult stage, makes a classification of internal/external parasitoids, did not observe oviposition by parasitoid but says he expects this to happen, **first correct European interpretation of phenomenon of insect parasitism** (see van Lenteren and Godfray, 2005)
1670/71	Martin Lister (Britain, 1639 - 1712) suggested in a letter published in the Philosophical Transactions of the Royal Society, that there are insects that lay eggs in other insects (see van Lenteren and Godfray, 2005)

circa 1675 Otto Marsilius (Holland, 1619 - 1678) tells Swammerdam how parasitoid eggs are laid in host insect (see van Lenteren and Godfray, 2005)

1678 Jan Swammerdam and Otto Marsilius (Holland) observation and description of complete life cylce of parasitoid on p. 709 of the *Book of Nature* posthumously published in 1738, **first European description of phenomenon of insect parasitism based on observation of complete life cycle** (see van Lenteren and Godfray, 2005)

1679 Maria Sybilla Meriam (Germany-Holland,1647 - 1717) *Der Raupen wunderbare Verwandelung,* observes emergence of parasitoid larvae from caterpillar, draws many parasitoids (see Vidal, and van Lenteren and Godfray, 2005)

1685 Martin Lister (Britain, 1639 - 1712) *De Insectis*, supposes that the larvae that Goedaert saw emerge from caterpiller had developed from eggs that were laid earlier by an insect in the caterpillar (see van Lenteren and Godfray, 2005)

1685-1691 Maria Sybilla Merian (Germany-Holland, 1647 - 1717) *Der Raupen wunderbare Verwandelung,* final version, 3 volumes, gives in the preface of this posthumously published version of 1717 a correct interpretation of insect parasitism based on obervation of egg laying by parasitoid, supposedly in period 1685-1691 (see van Lenteren and Godfray, 2005)

1686 Marcello Malpighi (Italy, 1628 - 1694) *Opera omnia*, observes ermergence of parasitoids but does not understand phenomenon of insect parasitism

l687 Antoni van Leeuwenhoek (Holland, 1632 - 1723) letter 59, observes larvae and adult parasitoids, supposes they developed from eggs laid in or on host by parasitoid, expresses the same opinion in several later letters, but did for a long time not see egg laying by parasitoid (see van Lenteren and Godfray, 2005)

1690-1705 John Ray (Britain, 1627 - 1705) interpretes phenomenon of insect parasitism correctly, but did not observe egg laying by parasitoid; his correct interpretation was posthumously published in his *Historia Insectorum* in 1710 (see van Lenteren and Godfray, 2005)

1692 Diacinto Cestoni (Italy, 1637 - 1718) sends letter to Vallisnieri in which he describes the attack of a whitefly by a parasitoid (see Tremblay and Masutti, 2005)

1696 Antonio Vallisnieri (Italy, 1661 - 1730) *Dialoghi, sopra la curiosa origine di molti insetti,* publishes a correct interpretation of insect parasitism, but did not yet observe oviposition by parasitoid (see Tremblay and Masutti, 2005)

1700 Antoni van Leeuwenhoek (Holland, 1632 - 1723); letter 134, describes in great detail the observation of oviposition and whole development of parasitoid based on experimentation, provides picture of parasitoid in position of attack (see van Lenteren and Godfray, 2005)

1702 D. Nomoto (Japan, 1665 - 1714) *Methods for Sericulture*, mentions tachinid parasitoid of silkworm, but does not know its biology (see Hirose, 2005)

1704 Pu Songling (China, 1640 - 1715) *Works of Mr. Liao Zai - Notes after Disaster*, observes emergence of hymenopteran parasitoid from caterpillar; did not see oviposition, probably first Chinese paper in which hymenopteran parastoid is described (see Wanzhi Cai et al., 2005)

1717 Maria Sybilla Merian (Germany-Holland, 1647 - 1717) *Der Raupen wunderbare Verwandelung*, final version, 3 volumes, preface to this version provides description of full cycle of insect parasitism based on observation of all stages supposedly made between 1685-1691 (see van Lenteren and Godfray, 2005)

Discovery of pathogens of insects

Diseases of silkworms were recognized as early as th 18th Century, although diseases of bees were known to the Greeks and the Romans. Many publications in the sixteenth, seventeenth and eighteenth century deal with diseases of silkworm, a very important industry at that time. Vallisnieri was the first to mention the muscardine disease of silkworm. De Reamur described and was the first to illustrate a fungus, *Cordyceps*, infecting a noctuid larva in 1726. The microbial nature of these diseases was not yet realized.

From William Kirby's chapter on "Diseases of Insects" (Vol. 4 (1826) of An Introduction to Entomology by Kirby & Spence) we learn that it was recognized that true fungi grew in the bodies of insects as saprophytes and possibly as parasites. Agustino Bassi was the first to experimentally demonstrate in 1837 that a microorganism, *Beauvaria bassiana*, caused an animal disease, namely the muscardine disease of silkworms. It was also Bassi who published the idea to use microorganimsm for insect pest control in 1836. Later, in 1874, Pasteur suggested the use of microorganisms against the grape phylloxera in France. These suggestions did not result in practical application.

Metchnikoff tried to develop biological control for the wheat cockchafer (*Anisopilia austriaca*) a serious pest of cereal crops in the area of Odessa, Russia. In 1879 he published a paper on *Metarrhizium anisopliae*, and his experiments led to the conclusion that the fungus, when mass produced, and properly introduced in the field might result in effective control. Based on Metchnikoffs work, *Metharrhizium* was mass produced in 1884 in the Ukraine, and the spores were tested in the field against a curculionid in sugar beet (*Cleonus punctiventris*).

To be added: information on bacteria, viruses, protozoa and nematodes

References

Aldrovandi, U., 1602. De Animalibus Insectis Libri Septem. Bologna. (in Latin)

Beier, 1973. The early naturalists and anatomists during the Renaissance and Seventeenth century. In: Smith, R.F., Mittler, T.E., Smith, C.N. (Eds.), History of Entomology, , Annual Reviews Inc., Palo Alto, California, pp. 81-94.

Cai, W.Z., Yan Y.H., Li, L.Y., 2004. The earliest records of insect parasitoids in China. Biological Control 32: 8-11.

Carton, Y., 2005. Reaumur (1683-1757): the discoverer of parasitoids in France. Biological Control 32: 40-48.

Chou, I., 1957. A History of Chinese Entomology in the Early Period. Science Press, Beijing. (in Chinese)

Gessner, C., 1634. Historia Animalum. (in Latin)

DeBach, P., 1974. Biological Control by Natural Enemies. Cambridge University Press, Cambridge: 323 pp.

Gurr, G., Wratten, S., 2000. Measures of Success in Biological Control. Kluwer Academic Publishers, Dordrecht.

Harpez, I., 1973. Early entomology in the Middle East. In: Smith, R.F., Mittler, T.E., Smith, C.N. (Eds.), History of Entomology, Annual Reviews Inc., Palo Alto, California, pp. 21-36.

Hirose, Y., 2005. Discovery of insect parasitism and subsequent development of parasitoid research in Japan. Biological Control 32: 49-56.

Kirby, W. & W. Spence, 1826. An Introduction to Entomology. Volume 4. Longman, Brown, Green and Longmands, London.

Konishi, M., Ito, Y., 1973. Early entomology in East Asia. In: Smith, R.F., Mittler, T.E., Smith, C.N. (Eds.), History of Entomology, Annual Reviews Inc., Palo Alto, California, pp. 1-20.

Lenteren, J.C. van, (Ed.), 2003. Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. CABI Publishing, Wallingford, UK.

Lenteren, J.C. van, 2005. Early entomology and the discovery of insect parasitoids. Biological Control 32: 2-7.

Lenteren, J.C. van , Godfray, H.C.J., 2005. European science in the Enlightenment and the discovery of the insect parasitoid life cycle in The Netherlands and Great Britain. Biological Control 32: 12-24.

Lenteren, J.C. van, Bale, J., Bigler, F., Hokkanen, H.M.T.and Loomans, A.J.M., 2006. Assessing risks of releasing exotic biological control agents of arthropod pests. Annual Review of Entomology, 51 (in press; available on internet from 1-10-2005).Lister, M., 1685. De Insectis. London. (in Latin)

Morge, G., 1973. Entomology in the Western world in antiquity and in medieval times. In: Smith, R.F., Mittler, T.E., Smith, C.N. (Eds.), History of Entomology, Annual Reviews Inc., Palo Alto, California, pp. 37-80.

Needham, J., 1956. Science and Civilisation in China. II. History of Scientific Thought. Cambridge University Press, Cambridge.

Needham, J., 1986. Science and Civilisation in China. VI. I. Botany, Cambridge University Press, Cambridge.

Reuter, O.M., 1913. Lebensgegewohnheiten und Instinkte der Insekten. Friedlander, Berlin.

Smith, R.F., Mittler, T.E., Smith, C.N., (Eds.), 1973. History of Entomology. Annual Reviews Inc., Palo Alto, California.

Tremblay, E., Masutti, L., 2004. History of insect parasitism in Italy. Biological Control 32: 34-39.

Vidal, S., 2004. The history of Hymenopteran parasitoid research in Germany. Biological Control 32: 25-33.

Wotton, E., 1552. De Differentiis Animalium Libri Decem. (in Latin)

3. Development of idea to use natural enemies for pest control and classification of types of biological control

First use of classical biological control (= use in inoculative releases)
Introduced alien pests often cause dramatic outbreaks and are presumed to have arrived without their natural enemies. In 1887, this led C.V. Riley to propose the introduction of natural enemies to control the cottony scale, *Icerya purchasi*, which had recently appeared in California and was devastating the newly established citrus industry. Natural enemies where found in Australia, transported to and released in California and saved the citrus industry from almost certain collapse (DeBach, 1964).

First use of augmentative biological control (= use in inundative and seasonal inoculative releases). Based on R.F. Luck and L.D. Forster, 2003. Quality of Augmentative Biological Control Agents: A Historical Perspective and Lessons learned from Evaluating *Trichogramma*. In: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK 231-246), and various other sources.

In Europe, R. Réaumur (in 1734) is supposed to be the first to propose the tactic to use insect predators for insect control: he adviced to release lacewings in greenhouses for the control of aphids. The notion of periodically releasing natural enemies was later suggested by F. Enock (1895) at a meeting of the London Entomological and Natural History Society. He suggested the possibility of "farming" *Trichogramma*. Flanders (1949) also credits Felix Gillet, the Horticulture Commissioner of California, with a similar notion. In an 1882 meeting in El Dorado, California, the Horticultural Commissioner stated that, "…it is surprising [given all the money spent to fight noxious insects that we] have never tried to raise ichneumon flies by the million and let them loose wherever there are any insect pests to destroy". Also Decaux, (1899) employed natural enemy releases as part of an integrated control tactic for fruit pests in France. Finally, Kot (1964, pg. 278) cites Radeckij as initiating experiments in 1911 on rearing and introducing *Trichogramma evanescens* Westwood for the control of *Cydia pomonella* (L.) (Lepidoptera: Tortiricidae). Radeckij collected the parasitoid from Astrakhan province in Turkistan and introduced it into Turkistani apple orchards. However, the first sustained use of augmentative biological control involved the suppression of the citrophilus mealybug, *Pseudococcus calceolariae* Fernald (Homoptera: Pseudococcidae), a pest of citrus in southern California, which began sometime between 1913 and 1917. The biological control agent, the coccinellid *Cryptolaemus montrouzieri* Mulsant (Coccinellidae: Coleoptera), initially introduced as a classical biological control agent, was unable to survive in sufficient numbers to affect control with out augmentation. This coccinellid is still being used in citrus to suppress mealybug pests and it is still commercially available. The initial success of this tactic led to an expansion in its use against other pests, beginning with the most widely used augmentative biological control

agents, *Trichogramma* species. Their use began in the late 1920's when S. E. Flanders developed a mass production system for them (Flanders, 1930).

First use of conservation biological control (=actions that preserve or protect natural enemies, Ehler 1998).
Until recently, conservation biological control has been the least well studied area of biological control (Ehler, 1998) and also the performance of conservation biological control has received little attention. This picture is changing quickly, however, and I refer to Gurr et al. (2000) for an extensive review of this area of biological control.
Conservation biological control has been used for several ages, but has been documented poorly. It was due to the use of chemical pesticides that the role of naturally occurring beneficial insects in pest reduction became clear. Spraying often resulted in reduction of the target pest, but could also result in the creation of secondary pests and resurgence of the primary pests when the natural enemy fauna was decimated as an effect of spraying. Understanding of this phenomenon made farmers and researchers aware of the need of more careful use of chemical pesticides, and this resulted in actions to protect natural enemies.

Two very well documented cases of conservation biological control relate to the development of integrated pest management in fruit orchards in North America and Europe, and they are summarized by Croft (1982) and Gruys (1982) respectively. An extensive multi-year study (1967-1995) in the Netherlands (Gruys, 1982; Blommers, 1994) clearly showed that over half of the 24 species of arthropod pests in apple orchards can be controlled fully or substantially by biological or cultural methods. Natural control was, however, disrupted in most of the orchards by extensive chemical sprays which became a routine procedure after the 1940s. Reintroduction of natural enemies from unsprayed orchards, use of selective pesticides and better timing of sprays resulted in restoration of the apple orchard ecosystem where natural control could function and where the number of pesticide sprays went down by 60-90%.

Well thought-out use of pesticides to safe natural enemies is just one example of conservation biological control; this form of biological control includes many more activities to preserve and protect natural enemies and these will be summarized elsewhere in this book.

Types of biological control

One may find many definitions of types of biological control in handbooks and articles, here we only present a few. In this book, we distinguish:

- classical biological control
- augmentative biological control
- conservation biological control

Classical biological control (= use of natural enemies in inoculative releases; usually, both the pest and the natural enemy are of exotic origin)

Classical biological control can often be summarized as follows (Bellows, 2005):

1. When a pest organism has invaded a new area, its population will grow until it occupies all available resources
2. If an effective natural enemy is released, it takes about 10-15 generations before it starts to reduce the pest population
3. The pest population is then reduced to very low numbers, usually 4-8 orders of magnitude lower than prior to natural enemy release; a control level unsurpassed by any other pest control method

4. Control is permanent, the pest and natural enemy continue to exist at very low densities without disruptions or outbreaks.

References:
Bellows, T., 2005. Reconstructing and ecosystem: a theory unifying invasion biology and biological control. Proc. Int. Symp. on Biological Control of Arthropods, 12-16 Sept. 2005, Davos, Switzerland. USDA Forest Service, Forest Health Technology Enterprise Team-2005-08, 1-13

Augmentative biological control (= use of natural enemies in inundative and seasonal inoculative releases). Based, among others, on unpublished information provided by R.F. Luck.

Augmentative biological control utilizes one to several releases of a natural enemy to suppress a pest during the course of a season or a crop's production cycle. Permanent establishment with consistent pest suppression in the absence of augmentation is not its aim. Frequently, augmentative releases are an outgrowth of an unsuccessful or partially successful effort to establish a natural enemy permanently, i.e. a classical biological control program (Smith and Armitage 1931, Flanders 1949). Under such circumstances, augmentative releases are meant to supplement an established complex of endemic and/or exotic natural enemy populations during critical periods when the natural enemy complex is incapable of suppressing the pest consistently on its own. It is seldom the case that a commodity, and the method under which it is grown, is devoid of such a complex, although the pest management practices applied in a particular circumstance can hamper the complex's effectiveness. Thus, augmentative biological control attempts to foster this complex with non-disruptive pest management tactics and to assist it with periodic releases of natural enemies and other non-disruptive tactics, i.e., integrated pest management. Augmentative biological control is one tactic in a pest management strategy that seeks sustainability in the management of a pest complex (e.g., Rabb et al. 1976, Flint and van den Bosch, 1981, Haney et al. 1992, Trumble and Morse 1993, Luck et al. 1997, van Lenteren, 2000).

Augmentative biological control has been used in several contexts. 1) It has been used as one or a few releases of large numbers of a natural enemy that seek to suppress the pest population immediately. This tactic is often referred to as inundative biological control. The release of *Trichogramma brassicae* Bezdenko (Hymenoptera: Trichogrammatidae)(= *T. evanescens* Westwood Maldavan strain Voegelé et al. 1975, or *T. maidis* Pint. and Voeg),

Containers with various species of mass produced natural enemies

against populations of the one or two generation, European cornborer, *Ostrinia nubilalis* Hübner, (Lepidoptera: Pyralidae) in northern Europe (Voegelé et al. 1975, Hassan 1981, Bigler 1986) is an example of such an approach. 2) It also has been used as a single release of a natural enemy that seeks to establish a population for the duration of a crop's growing cycle. This is often referred to as seasonal inoculative biological control (van Lenteren & Woets, 1988). A well documented Californian example of this tactic was the release, i.e., the seeding in, of endemic predatory mites, *Typhlodromus cucumeris* Oudemans or *T. reticulatus* Oudemans, against a strawberry pest, the cyclamen mite, *Phytonemus* (=*Steneotarsonemus*) *pallidus* (Banks), in the first year of a four-year production cycle, typical for this crop during the 1950's. Once seeded in, the mite predators remained on the plants and suppressed the cyclamen mite during the four-year production cycle (Huffaker and Kennett, 1953, 1956). This quadrennial production cycle, however, is no longer used commercially for strawberry production in California. 3) Finally, augmentative biological control has been used as multiple releases of a natural enemy to augment a population whose effectiveness has been constrained by seasonal climatic conditions affecting it or its host, or by disruptive factors, such as ants, dust, or pesticide use, in a perennial crop. In this case the pest population in the field can also serve as a field insectary, amplifying the released natural enemy population early in the season to affect season long suppression of the pest. This, too, has been referred to as inoculative biological control. An example of this tactic that involves field amplification is the long practiced spring releases of *Aphytis melinus* DeBach (Hymenoptera: Aphelinidae) to suppress California red scale, *Aonidiella aurantii* (Maskell) (Homoptera: Diaspididae) for the annual growing season in southern California (Lorbeer, 1971; Grabner et al., 1984; Moreno and Luck, 1992).

Augmentative biological control consists of three elements: 1) the mass production of an augmentative biological control agent(s) and its economics, 2) the agent's release and impact on a target's population density in the field, that is, the mechanics of release along with the ecology and population dynamics of the agent and its host or prey, and (3) the economics associated with pest suppression and crop production in a commodity in relation to the development of a sustainable pest management program at a specific geographical location.

Historically, many of the early “production systems” were an outgrowth of classical biological control efforts in which permanent establishment of the natural enemy was sought. When this goal failed, augmentative biological control evolved as a replacement or interim solution and the production system was adapted to this goal. This was the case for black scale on citrus in southern California. Black scale, inadvertently introduced around 1880, was one of several pests that threatened citrus’ early existence in southern California (Quayle, 1938; Graebner et al., 1984). It, along with several armored scale pests, was initially controlled with hydrogen cyanide fumigation (Quayle 1938). Trees infested with these pests where tented, and potassium or hydrogen cyanide gas was pumped into the tents for a period of approximately 50 min. (Quayle 1938). Such control, however, was expensive (Quayle, 1938; Graebner et al., 1984) and, at times, caused fruit or tree damage (Quayle, 1938). Also, as with most chemical approaches, black scale, along with another soft scale pest and several armored scale pests (Homoptera: Diaspididae), eventually developed resistance to this treatment (Quayle, 1938; Dickson, 1941). Thus, a classical biological control program was mounted, which led to the introduction of numerous parasitoids (Bartlett, 1977), the most important of which was *Metaphycus helvolus*, introduced from South Africa in 1937. It reduced black scale’s severity by 85 to 90 percent (Bartlett, 1977), but the scale still continued to be a sporadic pest of citrus in southern California.

The first use of the still most often used parasitoid in augmentative programmes, *Trichogramma*, of which we are aware, arose from an attempt to release and establish two exotic species from Austria for the control of the exotic brown-tail moth, *Nygmia phaerorrhoea* (Donovan) (=*Euproctis chrysorrhoea* L.) (Lepidoptera: Lymantridae) in the northeastern US during the early 1900’s (Howard and Fiske 1911; pp. 256-260). An endemic American *Trichogramma* species, *T. minutum* Riley (= *T. pretiosa* Riley, Pinto 1998) was also collected from brown-tail moth egg-masses in northeastern US. Both the American and European species were reared on brown-tail moth egg-masses and the parasitized eggs were stored at cool temperatures during the winter to synchronize their emergence with the presence of the moth’s egg-masses in the field. In 1908-9, large numbers of the European species were reared and released but, as expected from laboratory observations, these releases were unsuccessful. *Trichogramma* had difficulty penetrating the chorion of the moth eggs, or reaching the lower layers of the multi-layered, setae covered egg-mass.

It was the development of a mass-production system for *Trichogramma* by Flanders (1930), however, that spurred the use of these parasitoids as augmentative biological control agents. His development of a production system for this wasp was stimulated when codling moth eggs were detected as heavily parasitized by a *Trichogramma* sp. in 1926 in a southern California walnut grove. This level of parasitization was thought to have arisen from the presence of eggs of a migrating butterfly, the painted lady, *Vanessa cardui* L. (Lepidoptera: Nymphalidae), that laid its eggs on herbaceous species in spring, especially in disturbed habitats (Scott, 1986). Flanders assumed that the availability of these butterfly eggs early in the season allowed *Trichogramma* to parasitize and build up its density on them and then move onto codling moth eggs. Thus, Flanders reasoned, if these parasitoids could be reared in sufficient numbers early in the season and released to coincide with codling moth’s oviposition during the first generation, the moth might be suppressed to subeconomic densities (Flanders 1930). After testing several hosts on which to mass rear the wasp, including the Mediterranean flour moth, *Anagasta (Ephestia) kuehniella* (Zeller) (Lepidoptera: Pyralidae), the potato tuber moth, *Phthorimaea operculella* (Zeller) and the

Angoumois grain moth, *Sitotroga cerealella* (Oliver) (Lepidoptera: Gelechiidae), he chose *S. cerealella* eggs reared on wheat kernels for mass producing *Trichogramma*. The total production per unit weight of grain reached its maximum much more quickly with wheat than with corn kernels (Flanders, 1934). However, he maintained his small cultures on corn because they required less handling of equipment to maintain the small colony. Thus, the rearing system he employed depended on his rearing objective, a part of which sought to minimize rearing and maintenance costs. He eliminated *A. kuehniella* eggs as a host for *Trichogramma* because it was much more susceptible to larval parasitism and its webbing habits caused problems in handling the culture (Flanders, 1930). Better sanitary methods and rearing techniques have minimized these latter factors as problems and now *A. kuehniella* eggs are also used for mass production of *Trichogramma* (e.g., Voegelé et al., 1975, Bigler 1986). The eggs of these two moths are the principal hosts used to mass rear *Trichogramma* species except in the People's Republic of China (Smith 1996). Eggs of the giant silkworms, *Saamia cynthia* (Drury) and *Antherea perniyi* (Gnérin-Mádneville) (Lepidoptera: Saturniidae)), and the rice grain moth, *Corcyra cephalonica* (Lepidoptera: Pyralidae) are the principal hosts used in the People's Republic of China (Huffaker 1977).

Conservation biological control

In conservation biological control, the environment is manipulated or modified to improve the effectiveness of already established natural enemies through: (i) provision of missing or inadequate requisites such as alternative hosts, supplementary food or shelter; and (ii) by elimination or mitigation of hazards or adverse environmental factors such as poor cultural practices, indiscriminate use of insecticides and other adverse physical or biotic factors (see e.g. van Lenteren, 1987). One aims at protection, maintenance or increase of existing populations of biological control agents. Conservation of natural enemies has been suggested in Europe as early as 1827 by G.L. Hartig. Many attempts to augment existing natural enemy populations have been made thereafter, often on a local sale. Most are inadequately documented and are, therefore, not treated in any detail here (see e.g. Greathead, 1976).

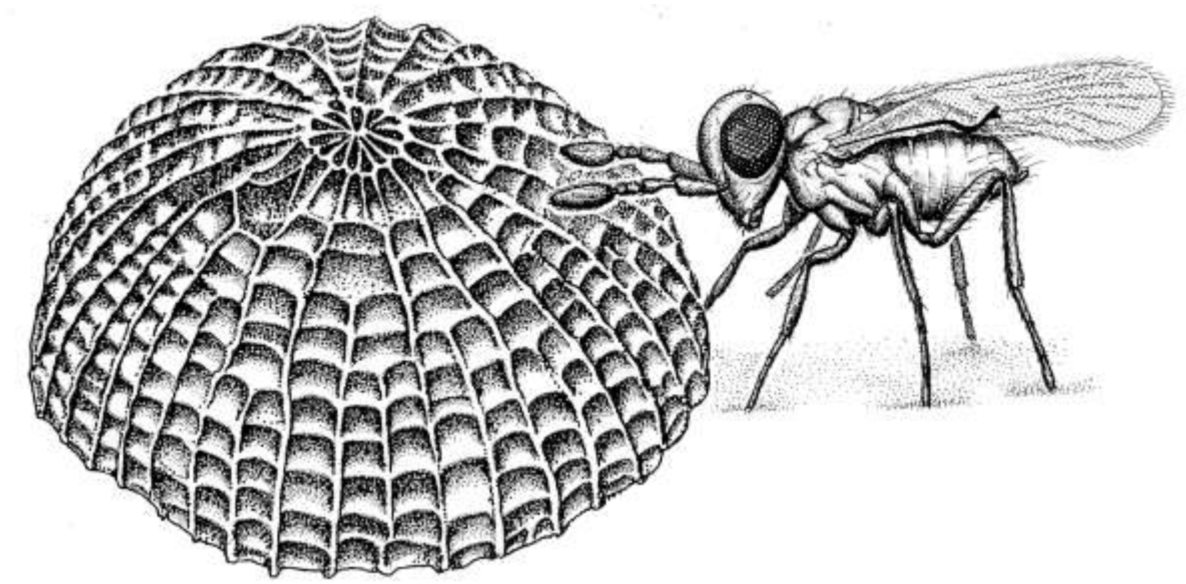
Beautiful examples of several aspects of conservation biological control is the IPM programme developed for pest control in fruit orchards in Europe (Blommers, 1994). A Dutch study clearly showed that over half of the 24 species of arthropod pests in apple orchards can be controlled fully or substantially by biological or cultural methods (Gruys, 1982). Reintroduction of natural enemies from unsprayed orchards to previously heavily sprayed orchards, use of selective pesticides and better timing of sprays resulted in restoration of the apple orchard ecosystem where natural control could function and where the number of pesticide sprays went down by 60-90% (Gruys, 1982).

An analysis of 51 recent studies to enhance conservation biological control (Gurr et al., 2000), showed that the vast majority of projects were successful in showing significant benefits for the natural enemies. However, a significant beneficial effect on natural enemies did not always result in a stronger reduction of pest populations or better yields. Because of the empirical approach that typifies many of these studies until now, effects of agroecosystem diversification on searching behaviour and success of arthropod natural enemies are still poorly understood and need to be studied with priority in order to be able to design fine tuned farming schemes that are based on pest pevention.

References:

Bartlett, B. R. 1977. Coccidae. Pp. 57-74. In C. P. Clausen (ed.) Introduced Parasites and Predators of Arthropod Pests and Weeds: A World Review. Agric. Handbook 480, U.S. Govn. Printing Office. Washington D. C.
Bigler, F. 1986. Mass production of Trichogramma maidis Pint. Et Voeg. and its field application against Ostrinia nubilalis Hbn. In Switzerland. J. Appl. Entomol. 101: 23-29.
Blommers, L.H.M., 1994. Integrated Pest Management in European apple orchards. Annu. Rev. Entomol. 39: 213-241.
Croft, B.A., 1982. Arthropod resistance to insecticides: a key to pest control failures and successes in North American apple orchards. Entomologia experimentalis et applicata 31: 88-110.
DeBach, P., ed. 1964. Biological Control of Insect Pests and Weeds. Cambridge Univ. Press, Cambridge: 844 pp.
Decaux, F. (1899) Destruction rationnelle des insects qui attaquent les arbres fruitiers par l'emploi simultanedes insectices, des insects auxiliaires, et par las prection et l'elevage de leurs ennemis natural les parasites. *Journal de la Société nationale d'horticulture de France* 22, 158-84.
Dickson, R. C. 1941. Inheritance of resistance to hydrocyanic acid fumigation in the California red scale. Higardia 13: 515-22.
Ehler, L.E., 1998. Conservation biological control: past, present and future. In: Conservation Biological Control, P. Barbosa (ed.), Academic Press San Diego: 1-8.
Enock, F. (1895) Remarks on *Trichogramma evanescens* Westw. Recorded by the Secretary of the South London Entomological and Natural History Society. *The Entomologist* 28: 283.
Flanders, S. E. (1930) Mass production of egg parasites of the genus *Trichogramma*. *Hilgardia* 4, 465-501.
Flanders, S. E. 1934. Storage production. J. Econ. Entomol. 27: 1197.
Flanders, S. E. (1949) Culture of entomophagous insects. *The Canadian Entomologist* 81, 257-274.
Flint, M. L. and R. van den Bosch. 1981. Introduction to Integrated Pest Management Plenum Press, New York. 240 pp.
Graebner, L., D. S. Moreno and L. L. Baritelle. 1984. The Fillmore Protective District: A success story in integrated pest management. Bull. Entomol Soc. Am. 30: 27-33.
Greathead, D.J., 1976. A Review of Biological Control in Western and Southern Europe. CAB, Farnham Royal: 182 pp. Contains an excellent history of biological control in Europe and describes most of the programmes developed for West and South Europe.
Gruys, P., 1982. Hits and misses: the ecological approach to pest control in orchards. Entomologia experimentalis et applicata 31: 70-87.
Gurr, G.M., S.D. Wratten & P.Barbosa, 2000. Success in conservation biological control of arthropods. In: Measures of Success in Biological Control, G. Gurr & S. Wratten (eds.). Kluwer Academic Publishers, Dordrecht: 105-132.
Haney, P. B., J. G. Morse, R. F. Luck, H. Griffths, E. E. Grafton-Cardwell, N. V. O'Connell. 1992. Reducing insecticide use and energy costs in citrus pest management. UC IPM Publ. 15. Univ. Calif. Div. Agric. Nat. Res. 62 pp.
Hassen, S. A. 1981. Mass-production and utilization of Trichogramma. 2. Four years of successful biological control of the European corn borer. Meded. Fac. Landbouww. Rijksuniv. Gent 46: 417-428.
Howard, L. O. and W. F. Fiske. 1911. The importation into the United States of the parasites of the gipsy moth and the brown-tail moth. U. S. Dept. Agric. Bur. Ent. Bull. 91: 1-312.
Huffaker, C. B. 1977. Augmentation of natural enemies in the People' Republic of China. Pp. 329-339. In: R. L. Ridgway and S. B. Vinson (eds). Biological Control by Augmentation of Natural Enemies. Plenum Press New York.
Huffaker, C. B. and C. E. Kennett. 1953. Developments toward the biological control of cyclamen mite on strawberries in California. J. Econ. Entomol. 46: 802-812.
Huffaker, C. B. and C. E. Kennett. 1956. Experimental studies onpredatuib: predation and cyclamen-mite populations on strawberries in California. Hilgardia 26: 191-222.
Kot, J. (1964) Experiments in the biology and ecology of species of the genus *Trichogramma* Westw. and their use in plant protection. *Ekologia Polska* Series A 12, 243-303.
Lenteren, J.C. van, 1987. Environmental manipulation advantageous to natural enemies of pests. In: Integrated Pest Management: Quo Vadis? V. Delucchi, ed. Parasitis 1986 Symposium Book, Geneve, Switzerland: 123-166.
Lenteren, J.C. van, 2000. Measures of Success in Biological Control Of Arthropods By Augmentation Of Natural Enemies. In: Measures of Success in Biological Control, G. Gurr & S. Wratten (eds.). Kluwer Academic Publishers, Dordrecht: 77-103.
Lenteren, J. C. van, and J. Woets. 1988. Biological and integrated control in greenhouses. Annu. Rev. Entomol. 33: 239-269.
Lorbeer, H. 1971. Integrated biological control in Fillmore citrus groves. Calif. Citrograph. (April)

Luck, R. F. L. D. Forster, and J. G. Morse. 1997. An ecologically based IPM program for citrus in California's San Joaquin Valley using augmentative biological control. Proc. Proceedings of the International Society of Citriculture VIII International Citrus Congress, May 12-17, 1996, Sun City, South Africa. 1:504-507.
Morino, D. S. and R. F. Luck. 1992. Augmentative releases of Aphytis melinus (Hymenoptera: Aphelinidae) to suppress California red scale (Homoptera: Diaspididae) in southern California lemon orchards. J. Econ. Entomol. 85: 1112-1119.
Pinto, J. D. 1998. Systematics of the North American species of Trichogramma Westwood (Hymenoptera: Trichogrammatidae). Mem. Entomol. Soc Washington. 22: 1-287.
Quayle, H. J. 1938. Insects of Citrus and Other Subtropical Fruits. Comstock Publ. Co. Inc. Ithaca New York. 583 pp.
Rabb, R. L., R. E. Stinner, and R. van den Bosch. 1976. Conservation and augmentation of natural enemies. Pp. 233-54. In: C. B. Huffaker and P. S. Messenger (eds). Theory and Practice of Biological Control. Academic Press New York.
Scott, J. A. 1986. The Butterflies of North America. Stanford Univ. Press. Stanford Calif.
Smith, H. S. and H. M. Armitage, 1931. The biological control of mealybugs attacking citrus. Calif Agric Exp Sta. Bull. 509
Smith, S. M. 1996. Biological control with Trichogramma: Advances, successes, and potential of their use. Ann. Rev. Entomol. 41: 375-406.
Trumble, J. T. and J. G. Morse. 1993. Economics of integrating the predaceous mite, Phytoseiulus persimilis (Acari: Phytoseiidae) with pesticides in strawberries. J. Econ. Entomol. 86: 879-885.
Voegele, J., M. Stengel, G. Schubert, J. Daumal, and J. Pizzol. 1975. Premiers resultats sur l'introduction en Alsace sous forme de lâchers saisoionniers de l'écotype moldave de Trichogramma evanescens Wests. contre la purale du maïs, Ostrinia nubilalis Hübner. Ann. Zool. Ecol. Anim. 7: 535-551.



Trichogramma sp. drumming Mamestra brassicae egg (drawing by P.J. Kostense, Wageningen University)

4. History of biological control

Below, information is presented for:
ATRS-IOBC: Africa South of the Sahara
NRS-IOBC: North Ameria
NTRS-IOBC: Latin America
WPRS-IOBC: Europe
History for several regions/countries needs to be written, information is available for:
Australia: several books and publications
Central and East Europe: books and publications
North America: several books, recent book edited by Mason

Early history of biological control

(this text is for a large part based on Greathead, 1994)
Prerequisites for a scientific approach to biological control were the general acceptance that insects do not arise by spontaneous generation (F. Redi in 1668), the appreciation of the importance of pests in reducing crop yields, the correct interpretation of behaviour and development of predators (circa 300 AD in China; see chapter discovery of natural enemies) parasitic insects (J. Swammerdam in 1678; see chapter discovery of natural enemies) and pathogens (W. Kirby in 1824; see Kribe & Spence, 1826), and evolution of the idea to use natural enemies in the control of pests. In Europe, R. Réaumur (in 1734) is supposed to be the first to propose this: he advised to release lacewings in greenhouses for the control of aphids.

During the 19th Century taxonomy strongly developed and many biological studies of natural enemies were made. Practical ideas and tests about application of biological control gradually advanced. It was Erasmas Darwin, the grandfather of Charles Darwin, who published a book on agriculture and gardening in 1800 (Phytologia) and in it he stressed the role of natural enemies in reducing pests. Moreover, he suggested to control aphids in hothouses by artificial use of predaceous syrphid fly larvae. Augmentation of ladybird beetles for control of hop aphis in the field and aphids in greenhouses was also suggested by Kirby & Spence (1815).

The first introductions of predators followed the colonisation of tropical islands by Europeans. Possibly the first successes followed the introduction of the Indian mynah bird, *Acridotheres tristis*, into Mauritius in 1762 for control of the red locust (*Patanga septemfaciata*) (Greathead, 1971). Other introductions were less successful, including the notorious introductions of the giant toad (*Bufo marinus*) from Cayenne into Cariibbean islands for control of white grubs (*Scarabaeidae*) in sugar cane fom 1830, and of the Indian mongoose (*Herpestes auropunctatus*) into Carabbean and Indian Ocean islands for rat control starting in 1870. These generalist predators were of some initial benefit, but later became pests and were implicated of the extension of endemic species of birds. After these “mistakes”, practioners of biological control have become careful and prefer to release specialist natural enemies, which do not attack useful organisms. The first of these more carefully planned introductions is believed to be that of a predatory mite, *Tyroglyphus phlloxerae*, from the USA into France in 1873 for control of phylloxera, but these releases were not successful.

The suggestion that parasitoids might be exploited for pest control was not made until 1856, when A. Fitch proposed introducing them against the European wheat midge, Contarinia tritici, in the USA. The first introduction did not take place until 1883 when *Cotesia glomeratus* was established in the USA for control of the cabbage butterfly, *Pieris rapae* (Greathead, 1994).

In 1835, the Italian A. Bassi showed that the infectious muscardine disease of silk worms was caused by a fungus known as *Beauveria bassiana*. Much later, in 1878, exploitation of fungi for pest control was attempted in Russia by E. Metchnikoff, when he began a culture of the green muscardine fungus (*Metarhizium anisopliae*) for control of the grain beetle, *Anisoplia austriaca*, and later for control of other beetles. Studies on silkworm diseases by L. Pasteur during 1856-1870 established bacteria as causes of insect diseases, but only one species was used in pest control inititally, *Bacillus thuringiensis*. It was first isolated in Japan (1901) and later again in Germany (1911). Successful commercial exploitation was achieved in the 1950s.

Biological control of weeds did not start until after 1850. The American entomologist Asa Fitch was the first to suggest biological control of weeds in about 1855, when he observed that a European weed in New York pastures had no American insects feeding on it. He suggested that importation of European insects feeding on this weed might solve the problem. The first practical attempt dates from 1863, when *Dactylopius ceylonicus* was distributed for cactus control in souther India after they had been observed to decimate cultivated plantings of the prickly pear cactus *Opuntia vulgaris* in northern India (Goeden, 1978). In 1865, the first successful international importation for weed control took place, when this same insect was transferred from India to Sri Lanka, where in a few years time widespread populations of the same cactus, *Opuntia vulgaris*, were effectively controlled.

Thus, by the late 19th century, knowledge was sufficient for the emergence of biological control. At that time, very few chemical pesticides were available, so the first applied entomologists had to be resourceful and use any effect pest control available, whether cultural, mechanical, biological or chemical. In fact, they practised something similar to what we call now Integrated Pest Management (IPM).

Until 1900 plants were often transported without carefully checking for potential pest organisms. Transport was on the decks of sailing ships and, to increase their chance of survival, in the Wardian Case (a portable greenhouse). However, pests were also easily transported in these cages on their target crop, and many pests had already become cosmopolitan before plant quarantine regulations were introduced at the end of the 19th century. Introduced pests often cause dramatic outbreaks and are presumed to have arrived without their natural enemies. In 1887, this led C.V. Riley to propose the introduction of natural enemies to control the cottony scale, *Icerya purchasi*, which had recently appeared in California and was devastating the newly established citrus industry. Natural enemies where found in Australia, transported to and released in California and saved the citrus industry from almost certain collapse. This success triggered more introductions of, mainly, ladybird species, but seldomly with the same control success. The outcome of these first years was (1) a realisation that not all natural enemies were capable of controlling a pest and (2) the beginning of the search for a scientific approach to biological control.

References

Goeden, R.D., 1978. Biological control of weeds. In C.P. Clausen, ed. Introduced Parasites and Predators of Arthropod Pests and Weeds: a World Review. Agric. Handbook No. 480. USDA, Washington, D.C.: 357-414.

Greathead, D.J. (1971) *A Review of Biological Control in the Ethiopian Region*. Commonwealth Institute of Biological Control, Technical Communication No. 5, Commonwealth Agricultural Bureaux, Farnham Royal. 162 pp

Greathead, D.J., 1994. History of biological control. Antenna 18 (4): 187-199.

Kirby, W. & W. Spence, 1815. An Introduction to Entomology. Longman, Brown, Green and Longmands, London.

Kirby, W. & W. Spence, 1826. An Introduction to Entomology. Volume 4. Longman, Brown, Green and Longmands, London.

History of biological control in Africa, the Afro Tropical Region Section (IOBC-ATRS)
(mainly based on Greathead, 2003; the permission of the author and the publisher (CABI) to use this material is gratefully acknowledged).

Introduction

This overview of biological control of pests (the term is used to include animals, pathogens and weeds) includes the area covered by the Afrotropical Zoogeographical Region, i.e., Africa south of the Sahara and the islands in the Indian and Atlantic Oceans closer to Africa than other continents. Before the European colonization, Indonesians are known to have reached the East African coast and Madagascar, and traded with the inhabitants. This trade may have been responsible for the introduction of some exotic pests like the Asian cereal stem borer, *Chilo partellus* (Swinhoe) and *Chilo sacchariphagus* (Bojer) together with its natural enemy, *Cotesia flavipes* (Cameron). European colonists also brought new crops and their associated pests, like many scale insects and soil pests.

A number of the pests that reached the region after World War II have been targeted for biological control. These include the cassava pests, *Mononychellus tanajoa* (Bondar) and *Phenacoccus manihoti* Matile-Fererro, introduced from South America on illegally imported planting material, *Liriomyza trifolii* (Burgess) which reached Kenya on chrysanthemum cuttings from Florida imported for multiplication and *Pineus boerneri* Annand is believed to have reached Africa on pine twigs imported for grafting. *Prostephanus truncatus* (Horn) arrived by sea in maize sent as famine relief. A notable example on the island of Mauritius is the south east Asian banana skipper (*Erionota thrax* (Linnaeus)) which almost certainly gained entry at the time of civil disturbances when troops were flown at night from Malaysia to help keep order.

Native pests have spread also and expanded their range with human assistance. The coffee mealybug, *Planococcus kenyae* Le Pelley, is an example, having spread into Kenya from Uganda. These too are sometimes good targets.

However, the majority of pests in Africa are native and many of them have a full complement of natural enemies which leaves few opportunities for classical biological control. Here methods for conservation or augmentation may be appropriate. The first applied entomologists appointed by the colonial governments became enthusiastic about the opportunities offered by introducing natural enemies which offered permanent control without the need for input from farmers.

In this review programmes are discussed which have been of particular significance in the development of biological control in Africa. Many of them are treated in detail in Neuenschwander et al. (2003) so that only brief mention is made here. Notably, the large number of successful biological control programmes against weeds in South Africa since the end of World War II, many of them of conservation importance, are not discussed because they are reviewed by Zimmermann & Olckers (2003).

The BIOCAT database (Greathead and Greathead, 1992 and updated to end 2001) contains records of introductions of insect natural enemies made against insect pests. The pattern of introductions and their successes for the Afrotropical Region are not very clear because too few data are available to be reliable indicators of a trend for the period 1890-1980. However both the world figures and the Afrotropical figures show a sharp increase in the rate of successful controls and establishments during the 1980s. The figures for the 1990s probably show the same trend but the final outcome of many of the successful introductions during this decade is not yet clear (for details and figures about successes, see Greathead, 2003).

Table 1 shows the countries of the Afrotropical Region that have made more than ten introductions and the number of insect pest species successfully controlled in each of them. It is of interest that those countries at the top of the table are ones that had early biological control successes. The results being obtained in Mauritius resulted in the neighbouring island countries starting biological control programmes. Similarly work in the eastern African countries was stimulated by successes in Kenya and also to some extent South Africa. It is notable that the only West African countries included in the table appear largely because of the unsuccessful campaign against *Planococcoides njalensis* (Laing) in Ghana and of *Liriomyza trifolii* in Senegal. Summary information for all successful biological controls of insect pests up to 1979 is provided by Greathead (2003; Table 2).

Information on biological control of weeds worldwide up to 1996 is contained in the fourth edition of the catalogue edited by Julien and Griffiths (1998) and for an overview of successful weed control projects, see Greathead (2003; Table 3). Weed biological control programmes show an increasing number of introductions each decade with the exception of the 1940s and steady establishment and success rates (species contributing to control). The trend towards increasing activity in biological control of weeds has continued with both the number of new releases and the number of new weed targets increasing in each five year period between successive editions (Julien and Griffiths, 1998). A frequently noted and important difference between insect biological control and weed biological control is the higher establishment rate (63%) and success rate (27.9%) for weeds as compared with rates for insects; 33.5% establishments and 11.2% successes (data from BIOCAT).

Table 1. Countries making more than ten introductions of insect biological control agents against arthropod pests (data from the BIOCAT database, Greathead 2003).

Country	**No. of introductions and (successful controls)**	**No. of pests**	**Year started**	
Mauritius	132 (10)	22	1913	
South Africa	106 (11)	32	1892	
Kenya	53 (6)	18	1911	
Ghana	47 (2)	5	1948	
Seychelles Islands	30 (6)	13	1930	
Madagascar	28 (3)	11	1948	
Cape Verde Islands	25 (2)	10	1981	
Uganda	24 (3)	9	1934	
Réunion	22 (4)	9	1953	
Zambia	22 (2)	6	1968	
St Helena	20 (4)	6	1896	
Sénégal	17 (1)	3	1954	
Tanzania	17 (3)	8	1934	
Comoros Islands	12 (0)	2	1969	

First attempts at biological control (1892-1920)

Documented biological control on the African continent began with the independent introductions of *R. cardinalis* into the Cape Colony in 1892. The introduction was made as a direct result of news of the outcome of its introduction into California. There followed a period of indiscriminate introduction of beneficial insects, chiefly ladybirds for aphid control, with little success. In eastern Africa, the first biological control attempt was made in Kenya in 1911 against an aphid, *Schizaphis graminum* (Rondani), which had first appeared in 1909-10 damaging the wheat crop, by introducing the parasitoid, *Lysiphlebus testaceipes* (Cresson) and the predator *Hippodamia convergens* (Guérin-Méneville), but neither is known to have become established. In West Africa biological control activity does not seem to have begun until after World War I, but even then was much less extensive than in other parts of the continent until the 1980s.

Biological control was the principal means for combating major pests in Mauritius, particularly in sugarcane where spraying with pesticides is both inefficient and uneconomic. On sugarcane the first target was a white grub, *Oryctes tarandus* (Olivier) native to Madagascar, which was readily controlled by introduction of its parasitoids, *Scolia oryctophaga* Coquillett (Hymenoptera: Scoliidae), imported from Madagascar in 1917. Less readily controlled was another white grub, *Phyllophaga smithi*, which had been accidentally introduced from Barbados with sugarcane varieties shipped in tubs of infested soil. Introduction of its parasitoids, *Tiphia parallella* Smith, from Barbados in 1915 did not provide control and a campaign followed to import and release parasitoids of other white grubs, principally from Madagascar, Indonesia, the Philippines, and South Africa, of some 42 species, chiefly Scolioidea and Tachinidae. Of these only 7 other species became established by the time work stopped in 1951 after a misguided attempt to introduce the giant toad, *Bufo marinus* (Linnaeus) (Amphibia: Bufonidae), from Trinidad which fortunately failed. By then the importance of the pest had declined, probably due to a combination of the results of breeding varieties better suited to the island and improved agronomic methods as well as the establishment of parasitoids. Other sugarcane pests were more readily controlled. The Seychelles and Madagascar began biological control after World War I but Réunion did not start until the 1960s.

Insects were targets for biological control of all the early efforts mentioned above. However, the earliest attempt to control a weed took place in South Africa when *Dactylopius ceylonicus* (Green) was obtained from the Queensland Prickly Pear Commission in 1913 and achieved spectacular control of *Opuntia vulgaris* Miller (Cactaceae) within a few years. Subsequent effort to control other *Opuntia* spp. in South Africa up to the 1950s followed the lead of Queensland.

The first attempts to use microbial agents took place in South Africa when in 1896 unsuccessful attempts began to culture and distribute fungal pathogens of locusts. Then in 1912 experiments were carried out on controlling grasshoppers with *Coccobacillus acridiorum* d'Hérelle (Bacteria) which, as in other countries, were a failure.

Activity was interrupted by the World War I. but several major programmes were carried out until the availability of DDT and other synthetic pesticides after World War II caused a temporary decline in interest in biological control. For details of all programmes see the comprehensive review of biological control activity in the Afrotropical zoogeographical region up to 1970 by Greathead (1971). Here only a few particularly significant programmes which influenced the development of biological control activity in African countries can be mentioned but see Table 2 in Greathead (2003) for a complete overview.

Major programmes and new insights (1920-1940)

After World War I response to the demand for biological control agents led to the setting up of the Farnham House Laboratory in 1927 under the Imperial Bureau of Entomology to find and supply biological control agents for the British Empire. In fact from the outset work was also carried out for other countries. The Farnham House Laboratory was directed by W.R. Thompson, a Canadian who had worked in France for the United States Department of Agriculture laboratory set up to find natural enemies for control of the gypsy moth (*Lymantria dispar* (Linnaeus)) in the USA. The Farnham House Laboratory was soon involved in supplying natural enemies to African countries and in assisting with several of the major biological control introduction programmes that were carried out until World War II.. W.F. Jepson was employed by the Laboratory to work with the Mauritius authorities on the campaign to control *Phyllophaga smithi*.

In Kenya, a landmark programme took place against a mealybug which began to devastate coffee plantations and food crops in the Kenya highlands in 1923. It was identified initially as *Planococcus lilacinus* (Cockerell) and efforts were made to obtain natural enemies from the native home of *P. lilacinus* in South and Southeast Asia. Many species were shipped to Kenya and cultures of natural enemies of other mealybugs were obtained from California, Hawaii and Japan but attempts made to culture them in quarantine failed. Partly as a result of these failures, it was realised that the mealybug was a new species, described as *Planococcus kenyae* Le Pelley. Unfortunately, early efforts with natural enemies from Uganda had failed and this delayed the discovery that the mealybug had originated in Uganda, north west Tanzania and the Congo. However, new importations from Uganda, made in 1938, included two species of *Anagyrus* (Hymenoptera: Encyrtidae) which readily bred on *P. kenyae* and rapidly established following releases in the same year. By 1949 control was good in almost all areas and incipient outbreaks were controlled by the release of parasitoids. The situation was disturbed during the early 1950s by the use of persistent chlorinated hydrocarbon insecticides to control other pests on coffee but was re-established when non-persistent insecticides replaced the chlorinated hydrocarbons. In 1959 it was estimated that some £10 million had been saved against an outlay of a total expenditure of not more that £30,000. This programme emphasised the need for accurate identification of the pest and the need to look in its native distribution area for effective natural enemies. It also supported the concept of J.G. Myers developed while working on biological control of sugarcane stem borers in the Caribbean using parasitoids from South America (Greathead, 1994) that ecological islands with high biodiversity exist within continental areas and are profitable places to search for natural enemies. This led the coffee research authorities in Kenya and Tanzania to fund research on biological control of coffee bugs, *Antestiopsis* spp., and leaf miners *Leucoptera* spp. during the 1960s (Greathead, 1971 and references therein). Unfortunately, no new and effective natural enemies of either of these two pests were found and insecticides continue to be applied for their control.

In South Africa an Australian weevil, *Gonipterus scutellatus* Gyllenhal, was first discovered attacking young growth in eucalyptus plantations in 1916. It remained largely confined to coastal areas until 1925 when it began to spread rapidly into the interior. Feeding by the weevil and its larvae destroys the tender young shoots causing poor growth and distortion of trees in plantations. An entomologist was sent to Australia, where the weevil is not a pest, and he soon found an egg-parasitoid, *Anaphes nitens* (Girault). This along with other parasitoids was shipped to South Africa but it was the only one to be successfully bred and released. By 1935 it had achieved economic control in all areas except the Highveld. Gradually the parasitoid seems to have adapted to the cooler conditions at higher altitudes as control has substantially improved. This success was achieved against predictions that egg-parasitoids are less effective than natural enemies of the later stages. It has also been repeated elsewhere wherever the parasitoid has been released, including East Africa, Madagascar, Mauritius and St Helena (Greathead, 1971 and references therein).

In Mauritius, pest control of sugarcane white grubs dominated biological control activity during the interwar period (see above). In the Seychelles a complex of scale insects on coconuts (principally *Eucalymnatus tessalatus* (Signoret), *Chrysomphalus ficus* Ashmead, *Ischnaspis longirostris* (Signoret) and *Pinnaspis buxi* Bouché) were the most important insect pests and in 1936 investigations began. As there were no effective native natural enemies, coccinellid predators were introduced from East Africa and India. *Chilocorus distigma* (Klug) and two species of *Exochomus* from Africa and *C. nigrita* (Fabricius) from India became established. The results were spectacular, with control achieved in a matter of months and a substantial increase in the coconut crop from 1940 onwards. *C. nigrita* became the most abundant species and remains so. It was also introduced from Sri Lanka into Mauritius in

1939 for control of another scale insect on coconuts, *Aspidiotus destructor* Signoret. It has proved to be a good colonist and has reached the African mainland and is now well established in East Africa and in southern Africa (Samways, 1989).

During this period a major effort was made in South Africa to control prickly pear cactus (*Opuntia* spp.). *Dactylopius* spp. were also introduced into Mauritius in 1928 and provided good control until the establishment of the Australian coccinellid, *Cryptolaemus montrouzieri* Mulsant, in 1938 for control of the pineapple mealybug, *Dysmicoccus brevipes* (Cockerell). No recoveries were made on pineapple but by 1950 it was affecting control of cactus, as it did in South Africa, and *Cactoblastis cactorum* (Bergroth) was introduced to maintain control (Greathead, 1971). Otherwise there were no significant efforts to control weeds during this period.

The response to synthetic pesticides (1940-1970)

At the end of World War II new powerful, broad spectrum synthetic pesticides became available for agricultural use and in many countries biological control was abandoned as a result. Many of the remaining biological control practitioners responded by trying to demonstrate that biological control was cheaper and provided permanent control. At the same time air transport was becoming universal and for the first time consignments of natural enemies could be sent across the world as eggs or pupae in a few days at most, instead of several weeks on ships when they frequently required the attendance of an entomologist to maintain the culture. Consequently, it was tempting to economise on detailed ecological studies and the development of methods for laboratory culture by shipping large numbers of agents for direct release on arrival. In this way it was possible to send numbers of species, release them and see whether they became established instead of sending one or a very few carefully studied species for multiplication and release. Thus, the lessons learned in the preceding period were forgotten and the success rate fell, with the result that instead of promoting biological control it acquired a reputation of being unlikely to succeed and at best a last resort to be considered only if all else failed.

Dr Thompson and some of the staff of the Farnham House Laboratory went to Canada to continue their work in 1940 and after the war the service became the Commonwealth Institute of Biological Control (CIBC). Work in developing countries was expanded and an East African Station opened in 1962 in Uganda and a West African Substation in Ghana in 1969 (Greathead, 1994). The purpose of these was to assist African countries and to find natural enemies for export to other regions. In francophone West Africa, Madagascar and Réunion biological control programmes started to be undertaken by staff of l'Institut de Recherches Agronomiques Tropicales (IRAT) and l'Office de la Départment de Recherche Scientifique d'Outre-Mer (ORSTOM) (Jourdheuil, 1986).

One target for biological control was the potato tuber moth, *Phthorimaea operculella* (Zeller), a native of South America which has become a major pest of potato, tobacco and other solanaceous crops throughout the warm temperate and tropical zones of the world. Efforts to find biological control agents began as long ago as 1918 with the importation and release of North American parasitoids in Europe and South Africa but these were ineffective. Exploratory research showed that South America was the native home of the insect and natural enemies from there appeared to have greater potential for biological control. Introduction programmes were carried out in most countries active in biological control, many of them with the assistance of CIBC which maintained cultures at its Indian Station at Bangalore. These included most anglophone southern and eastern African countries, Madagascar, Mauritius and the Seychelles. Only Zambia and Zimbabwe claimed spectacular results but the practicability of relying on biological control is in doubt.

The campaign against cereal and sugarcane lepidopterous stem borers in a number of countries, which took place during the 1950s and 1960s, is typified by the campaign in Mauritius. However, although one stem borer, *Sesamia calamistis* Hampson, was controlled by introduction of its parasitoid, *Cotesia sesamiae* (Cameron), from Kenya in 1951, importations of parasitoids of other genera of stem borers principally from India and Trinidad against the most damaging borer, *Chilo sacchariphagus*, during 1940-1965 failed to result in a single species becoming established although earlier introductions of parasitoids of other *Chilo* spp. from Sri Lanka in 1939 had at least resulted in establishment although none had any impact on the stem borer problem. In 1961 efforts began to obtain parasitoids of *C. sacchariphagus* from Java, although these efforts had included a major effort involving the breeding and release of more than 62,000 individuals of a parasitoid, *Diatraeophaga striatalis* Townsend. This parasitoid was also introduced into Réunion where some 80,000 flies were released but again without becoming established (Greathead, 1971 and references therein). This negative result contrasts with those achieved in the New World tropics where tachinid parasitoids have successfully controlled the major pest, *Diatraea saccharalis* (Fabricius) (Lepidoptera: Pyralidae) in a number of countries (Cock, 1985) and justified the effort made to establish *Diatreaophaga striatalis*. *S. calamistis* was also controlled in Madagascar by *Pediobius furvus* (Gahan) imported from East Africa in 1969 (Greathead, 1971). In East Africa and South Africa detailed ecological studies preceded introductions but even then no results were obtained at the time. In francophone West Africa releases of parasitoids cultured in France were made but little detail has been published. The results of all these studies were comprehensively reviewed by the contributors to Polaszek (1998).

The importation of a predatory mite, *Bdellodes lapidaria*, found to be effective against the lucerne flea (*Sminthurus viridis* (L) in Australia, into the Western Cape in South Africa was aimed at controlling the pest in cultivated legume based pastures. Over 78,000 mites were released between 1963 and 1966 and successful establishment and significant impact on pest numbers were achieved.

The Asian rhinoceros beetle (*Oryctes rhinoceros* (Linnaeus) Coleoptera: Scarabaeidae)) appeared in Mauritius in 1962 near the Port Louis docks, suggesting that it had arrived on shipping. During the following decade it spread across the island destroying coconut and ornamental palms. Introductions of insect natural enemies failed to check it, as on Pacific Islands where it was eventually controlled by introduction of a host specific virus. In 1970 this virus was introduced into Mauritius and rapidly brought the beetle under control. This example is interesting as one of the few instances where an insect pathogen has proved to be an effective classical biological control agent. An African species of rhinoceros beetle (*O. monoceros* (Olivier)) is a pest in the Seychelles Islands. Insect natural enemies also proved ineffective in controlling this species and in 1981-3 an attempt was made to use the *O. rhinoceros* virus to control it. It infected *O. monoceros*, became established in the field and caused a substantial reduction in damage levels but the infection rate and the degree of control was less than for *O. rhinoceros*.

In Ghana after it was established that the native mealybug, *Planococcoides njalensis*, was the principal vector of swollen shoot disease of cacao and that its own natural enemies did not provide adequate control, efforts were made to import and establish natural enemies of other species. These included species shipped from California, Trinidad and Kenya during 1948-55. Since early direct releases into the field failed, parasitoids were mass reared and released during the later years of the programme. In all some 880,000 individuals of ten species were released to no avail before the programme was abandoned (Greathead, 1971).

Another programme in which relatively large numbers of inappropriate natural enemies were released without success was the attempt to control the Karoo caterpillar, *Loxostege frustalis* Zeller, a serious pest of sweet Karoo bush, *Pentzia incana* Druce

(Asteraceae), following ecological changes resulting from overgrazing by sheep. In this instance parasitoids of the congeneric beet web worm, *L. sticticalis* (Linnaeus), were obtained from the USA and released directly into the field during 1942-50 without any recoveries in follow up surveys during the two seasons after releases ceased. In addition, one of the parasitoids, *Chelonus insularis* (Cresson) was mass-reared on a factitious host, *Ephestia kuehniella* Zeller (Pyralidae). In spite of problems with disease, just under 6 million were reared and released during 1942-54. Initial claims of recoveries were discounted when it was discovered that they related to a similar native species, not previously recorded from the Karoo caterpillar (Greathead, 1971).

Most new initiatives for the biological control of weeds during this period largely consisted of introducing agents that became available as a result of research for countries in other regions. As well as continuing efforts to control prickly pear cactus, introductions were made in East, South and West Africa and the Indian Ocean Islands for control of *Lantana camara* Linnaeus and in South Africa for control of *Hypericum perforatum* Linnaeus (Julien and Griffiths, 1998). However, alongside research on stem borers in cereals, studies on insects affecting witchweeds (*Striga* spp.) were carried out by the CIBC in East Africa. New initiatives were also being made to discover biological control agents for control of woody weeds, mostly of Australian origin, that were displacing native vegetation in South Africa. This work has led to the introduction of some very effective agents which are now controlling several of these plants very effectively (Julien and Griffiths, 1998).

Highly successful control resulted from the campaign in Mauritius to control the weed *Cordia curassavica* (Jacquin) Roemer and Schultes, an invader from the Caribbean which had developed dense thickets that were displacing pasture and natural vegetation. Research in Trinidad resulted in the introduction of two leaf feeding chrysomelid beetles in 1947. One of them, *Metrogaleruca obscura* (Degeer), became established and by 1950 much of the scrub was dying and continued defoliation was reducing its competitive power. To combat recolonisation, seed destroying insects were studied and one, *Eurytoma attiva* Burks, was selected for introduction and successfully established. Together these two agents have reduced the status of *C. curassavica* to that of a minor roadside weed (Greathead, 1971; Julien and Griffiths, 1998).

New approaches to biological control and IPM (1970-2000)

By the 1970s realisation of the disadvantages of sole reliance on synthetic pesticides had resulted in moves towards developing integrated pest management (IPM) programmes in which biological control was a major component.

Citrus pests in southern Africa provide one of the first examples of the development of IPM in Africa. Scale insects are major pests of citrus wherever it is grown and the crop has been the subject of biological control programmes around the world. This started in California with the control of *Icerya purchasi* and eventually resulted in the development of IPM programmes in which biological controls suppress all the scale insects. In South Africa the success with *I. purchasi* was followed by haphazard and unsuccessful introductions of ladybirds. Interestingly, one of them, *Cryptolaemus montrouzieri,* only became established as an effective predator of *Planococcus citri* (Risso) in 1939 when *Dactylopius* spp. had been established for control of *Opuntia* spp., provided alternative hosts, and annual releases were no longer required. Following the lead of California, *Aphytis* spp. were imported and successfully controlled *Chrysomphalus ficus* and *Lepidosaphes beckii* (Newman) but species introduced for control of *Aonidiella aurantii* (Maskell) failed to become established. However, pioneering work by E.C.G. Bedford showed that *A. aurantii* is suppressed by the native *Aphytis africanus* Quednau and, provided indiscriminate insecticide applications cease and steps are taken to control ants, IPM can be successful.

Renewed confidence in biological controls also led to an end to the practice of haphazard shipment of natural enemies at minimal cost and a return to well funded research programmes involving the selection and careful study of candidate biological control agents for control of arthropod pests prior to their introduction. This had long been done in weed control programmes where the prevention of damage to economically important plants was a prime concern.

The establishment of the International Institute of Tropical Agriculture at Ibadan in Nigeria in 1967, principally concerned with the breeding of improved crop varieties, eventually provided a new focus for pest management and biological control in tropical Africa, especially West Africa which had been the least active. The first of a new generation of international biological control programmes developed following the discovery of a mite, *Mononychellus tanajoa*, on cassava in Uganda in 1971 and a mealybug, *Phenacoccus manihoti* in 1973 in the Congo. Both new pests come from South America and are believed to have reached Africa on smuggled planting material. The CIBC soon obtained funding for research on their natural enemies in Trinidad and South America but the IITA was designated to carry out implementation of biological control. This began in 1980 with the appointment of H. Herren to lead the programme, which became the largest and most costly biological control programme ever undertaken. Outstanding control of *P. manihoti* was obtained with the encyrtid parasitoid, *Apoanagyrus lopezi* De Santis shipped to IITA in 1981 through a newly established CIBC quarantine facility in the UK. Progress with controlling the mite was slower and less dramatic than with the mealybug, and only began to succeed once the climates of the source area in South America and the infested areas of Africa were carefully matched and predators were obtained from areas of north west Brazil with a similar climate. However, the most successful species, *Typhlodromalus aripo* DeLeon, is confined to shoot tips and so allows persistence of the host population and is also better able to survive on alternative sources of food when *M. tanajoa* is scarce. It is now established in some twenty countries and has reduced mite damage by more than 50%. This narrow climatic dependency contrasts with *A. lopezi* which came from Paraguay and southern Brazil, yet was rapidly successful throughout the range of climates of the infested areas in Africa.

The confidence in biological control in West Africa generated by the success with *P. manihoti* enabled rapid progress in mounting a programme for control of the mango mealybug, *Rastrococcus invadens* Williams, when it appeared in Togo and Ghana in 1982. An encyrtid parasitoid, *Gyranusoidea tebygi* Noyes, was found in its native home in India, quarantined, released and had suppressed the mealybug in Togo within two years. Subsequently, the mealybug has been controlled throughout the area which became affected by *G. tebygi* and another encyrtid *Anagyrus mangicola* Noyes, which is the more important agent in urban areas.

There was also renewed interest in controlling cereal stem borers at the International Centre for Insect Physiology and Entomology (ICIPE) in Nairobi, which had been initiated by T.R. Odhiambo in 1970. This programme initially explored intercropping and methods of enhancing existing natural enemies but also undertook a concerted, and eventually successful, attempt to introduce the parasitoid *Cotesia flavipes*, for control of the major immigrant pest species *Chilo partellus*. Previous attempts to introduce this parasitoid by CIBC in 1968-72 in Uganda and Kenya and by South African entomologists in 1983-85 had failed (Polaszek, 1998).

Other collaborative programmes also developed, including a regional programme against forestry pests in tropical Africa which was coordinated by the International Institute of Biological Control (formerly CIBC) from its Kenya Station, set up in 1980 to replace the former East African Station in Uganda which was closed in 1979. The appearance of a devastating attack on ornamental and plantation cypresses in Malawi in 1985 and later Kenya and Tanzania by an immigrant aphid, *Cinara cupressi* (Buckton), stimulated the development of a regional programme to find biological control for this species. Interest was also renewed in controlling *Pineus boerneri* which had appeared in Kenya on exotic pine plantations in the 1960s, and after the failure of an eradication programme, had been the subject of an earlier unsuccessful biological control programme. This aphid had spread in the meantime and had reached as far south as the northern provinces of South Africa.

The floating water weed water hyacinth (*Eichhornia crassipes* (Martius) Solms-Laubach), which originated in South America and has been spread by horticulturists throughout the tropics on account of its showy flowers, has long been present on the African continent. This weed had been controlled successfully on the River Nile in the Sudan during the 1970s by introduction of insect control agents. Although present on several other rivers, it did not attract international attention until it invaded Lake Victoria down the Kagera River from Rwanda. Its rapid spread in the lake threatened fisheries, transportation and the hydroelectric power station at Jinja in Uganda where the River Nile leaves the lake. The IIBC Kenya Station was also involved with the FAO in developing an international campaign against it, but action was delayed by disagreements among the three riparian countries (Kenya, Tanzania and Uganda) on priorities and on the safety of biological control. This has eventually been implemented with very promising initial results. Later the Kenya Station became part of a wider initiative to develop a mycoherbicide to complement the action of insect agents, the International Mycoherbicide Programme for *Eichhornia crassipes* Control in Africa (IMPECCA) also including South Africa, Malawi, Nigeria, Benin and Egypt. Insect control agents had already been established in these countries but had not always been as successful as was hoped.

Another invasive pest, the larger grain borer (*Prostephanus truncatus*), which appeared in Tanzania in 1981 and shortly afterwards in Togo, spread into neighbouring countries causing devastating damage to stored maize and other crops. Major research programmes were initiated in West Africa in collaboration with the German Gesellschaft für Technische Zusammenarbeit (GTZ) and in East Africa with the British Natural Resources Institute (NRI). When it was realised that the beetle was breeding in natural habitats the possibility of biological control was considered. Field studies in its native home in Mexico detected a histerid predator, *Teretrius nigrescens* (Lewis). Unexpectedly, it was attracted to *P. truncatus* pheromone traps and *P. truncatus* was shown to be, at least, a preferred host, if not its only host, and so a potential biological control agent. Releases have been made in both East and West Africa where it is now well established. Its presence is linked to substantial reductions of *P. truncatus* in natural habitats and so colonisation of grain stores has been reduced.

Classical biological control of pests of medical and veterinary importance has seldom been successful but stable flies that were a serious constraint on dairy farming in Mauritius have been substantially controlled by introduced parasitoids. Puparial parasitoids of dung breeding flies were introduced in 1966-72 but did not solve the problem. Intensive surveys showed that they had in fact greatly reduced numbers of the dung breeding species, *Stomoxys calcitrans* (Linnaeus), but had not affected numbers of another species *S. niger* Macquart which was found breeding in rotting sugarcane tops. Studies in Uganda, started as part of a worldwide survey of filth fly natural enemies, showed a substantially different parasitoid spectrum of *Stomoxys* spp. breeding in rotting vegetation to that found in dung pits. When the parasitoids from puparia in rotting vegetation were introduced during 1975-78 a substantial drop in stable fly numbers took place and numbers remain at an acceptable level during most of the year.

Perhaps the most innovative biological control programme was initiated in 1989 for the control of locusts and grasshoppers. The desert locust (*Schistocerca gregaria* (Forskål)) outbreak of 1986-88 coincided with the banning of dieldrin which had been the mainstay of locust control since the 1960s. The FAO sought suggestions for novel environmentally benign control measures and supported the funding of work on semiochemicals at ICIPE and the development of a biopesticide by a consortium of IIBC, IITA and Département de Formation en Protection Végétaux (DFPV) of the Comité permanent Inter-Etats de Lutte contre la Sécheresse au Sahel (CILSS) which came to be known as LUBILOSA. The biopesticide programme investigated the proposition that fungi provided the best possibility of biological control using spores formulated in oil. This was based on the observation by C. Prior that oil formulations overcome the requirement that high humidity is needed for the germination of spores of entomophagous fungi (Prior and Greathead, 1989). The concept proved to be viable and eventually resulted in the registration of a product, Green Muscle, based on a strain of the green muscardine fungus with a narrow host range, *Metarhizium anisopliae* var. *acridum* Driver and Milner, for locust control in South Africa and subsequently elsewhere. The discovery opens the way for the development of other biopesticides based on entomophagous fungi for the control of other arthropod pests such as termites.

Most biological control research in Africa has aimed at achieving classical biological control as a first objective. However, there are numerous serious pests native to Africa which do not offer obvious opportunities for this approach. For example, research on natural enemies of the boll worm *Helicoverpa armigera* (Hübner) in Africa, Asia and Australia had shown few gaps in indigenous natural enemy spectra which could be exploited. Consequently, a new initiative was launched in 1987 to look for alternatives. The CIBC Station in Kenya undertook studies on natural enemy impact on a range of important crops with the objective of exploring their potential for enhancement in IPM (van den Berg, 1993). Similarly, cowpea pests have been a target for IPM exploiting natural enemies including a possibly adventive parasitoid (*Ceranisus femoratus* Gahan) which appeared in Cameroon in 1998 and has been redistributed to Benin.

In Kenya, coffee is a crop where biological control has been important since biological control of the mealybug *Planococcus kenyae* was implemented. This was overlooked in the 1950s when persistent organochlorine insecticides were applied for the control of antestia bugs (*Antestiopsis* spp.). Not only did this cause resurgence of mealybugs but also outbreaks of leafminers (*Leucoptera* spp.) which had been suppressed by their native natural enemies. A change to non-persistent organophosphate insecticides timed to coincide with peak adult leafminer numbers allowed biological control of mealybug to be re-established. However, spraying of copper fungicides for control of coffee berry disease was implicated in initiating outbreaks of a native species, *Icerya pattersoni* Newstead, in the early 1980s. Investigations showed that the principal natural enemy is a ladybird, *Rodolia iceryae* Janson, and efforts by growers to conserve this ladybird and other natural enemies resulted in a reduction in numbers of *I. pattersoni* by the end of the decade.

During the 1980s there was increasing concern about the impact of introduced species on natural ecosystems and, in particular, criticism of the impact of past introductions of biological control agents on non-target species, and a demand for more stringent screening of potential classical biological control agents prior to importation and release. One response was the convening of a an expert consultation by the FAO in 1991 which drafted a Code of Conduct for the import and release of exotic biological control agents which was published in 1996 (FAO, 1996). This is followed by agencies involved in the introduction of biological control agents into Africa, many of whom were represented at the expert consultation, notably the Inter-African Phytosanitary Council (IAPSC) whose country members have responsibility for approval of introductions of biological control agents into African countries. Biological control in Africa has also been affected by the Agenda 21 of the Rio Earth summit of 1992. As a result of these developments African governments are much more aware of biological control and biological control agents are being more thoroughly tested and evaluated before importation and release of exotic species is permitted. This will also ensure that in the future fewer but better researched agents are imported and will hopefully result in a higher success rate for introductions. Greater environmental awareness should also provide a spur to the development of IPM systems minimising the use of broad spectrum chemicals and making greater use of indigenous biological control agents and biopesticides. However, concern for the environment and the preservation of biodiversity needs to be tempered by the realities of African agriculture, which remains predominantly the concern of resource poor farmers. As eloquently argued by Neuenschwander and Markham (2001), the regulatory framework should not be made so prescriptive and cumbersome that biological control is replaced by more destructive alternatives, such as broad spectrum chemical pesticides, which few farmers can afford or are equipped to use safely (see also the chapter in this internet book on Legislation and regulation of biological control agents).

However, classical biological control is providing a benign means of limiting the damage done to natural ecosystems and endangered species by exotic pests. Progress in the control of invasive plants, principally from Australia, threatening the unique South African fynbos vegetation is discussed elsewhere by Zimmermann & Olckers (2003). A further example is the control of the polyphagous cosmopolitan scale insect *Orthezia insignis* Browne in St Helena where it was threatening the survival of the national tree, the endemic gumwood, *Commidendrum robustum*. Serendipitously, the scale had already been controlled in East Africa in the 1950s when it was causing severe nuisance by damaging urban flowering trees, especially jacaranda (*Jacaranda mimosiflolia* G. Don), by introduction of a ladybird, *Hyperaspis pantherina* Fürsch from Trinidad, since shown to be specific to the genus *Orthezia*. Thus, it was relatively straightforward to obtain the ladybird from Kenya for quarantining and introduction into St Helena where it has provided very successful control.

Although there remain opportunities for classical biological control, and no doubt more will occur as a result of accidental introductions of pests and invasive species, the principal need is for IPM schemes optimising the impact of indigenous natural enemies. This will, most likely, take the form of measures to conserve and enhance the action of arthropod natural enemies and the development of selective biopesticides for application as sprays or dusts.

References

Cock, M.J.W. (ed.) (1985) *A Review of Biological Control of Pests in the Commonwealth Caribbean and Bermuda up to 1982*. Commonwealth Institute of Biological Control, Technical Communication No. 9, Commonwealth Agricultural Bureaux, Farnham Royal. 218 pp.

Greathead, D.J. (1971) *A Review of Biological Control in the Ethiopian Region*. Commonwealth Institute of Biological Control, Technical Communication No. 5, Commonwealth Agricultural Bureaux, Farnham Royal. 162 pp.

Greathead, D.J. (1994) History of biological control. *Antenna* 18(4), 187-199.

Greathead, D.J., 2003. Historical Overview of Biological Control in Africa. In: Biological Control in IPM Systems in Africa, P. Neuenschwander, C. Borgemeister & J. Langewald (eds). CABI Publishing, Wallingford, UK, pp. 1-26.

Greathead, D.J. and Greathead, A.H (1992) Biological control of insect pests by insect parasitoids and predators: the BIOCAT database. *Biocontrol News and Information* 12, 61N-68N.

Jourdheuil, P. (1986) La lutte biologique á l'aide d'arthropodes entomophages. Bilan des activités des services français de recherche et de développement. *Cahiers de Liason O.P.I.E.*, 20(2) no. 61, 3-48.

Julien, M.H. and Griffiths, M.W. (1998) *Biological Control of Weeds: a World Catalogue of Agents and their Target Weeds*. *Fourth Edition*. CABI Publishing, Wallingford.

Neuenschwander, P and Markham, R. (2001) Biological control in Africa and its possible effects on biodiversity. In: Wajnberg, E., Scott, J.K. and Quimby, P.C. (eds.) *Evaluating Indirect Effects of Biological Control*. CABI Publishing, Wallingford, pp. 127-146.

Neuenschwander, P, C. Borgemeister and J. Langewald, (eds.) 2003. Biological Control in IPM Systems in Africa. CABI Publishing, Wallingford, UK, 414 pp.

Polaszek, A. (1998) *African Stem Borers: Economic Importance, Taxonomy, Natural Enemies and Control*. CAB International, Wallingford, 530 pp.
Prior, C. and Greathead, D.J. (1989) Biological control of locusts: the potential for the exploitation of pathogens. *FAO Plant Protection Bulletin*, 37, 37-48.
Van den Berg, H. (1993) *Natural control of Helicoverpa armigera in smallholder crops in East Africa*. PhD Thesis, Agricultural University, Wageningen. 223 pp.
Zimmermann, H.G. and T. Olckers, 2003. Biological control of alien plant invaders in southern Africa. In: Biological Control in IPM Systems in Africa, P. Neuenschwander, C. Borgemeister & J. Langewald (eds). CABI Publishing, Wallingford, UK, pp. 27-44.

History of biological control in North America, the Nearctic Regional Section (IOBC-NRS)

By 1850 biological control obtains full attention in the USA, where imported pests were taken a large toll of (often also) imported crops. Entomologists (e.g. Asa Fitch, C.V. Riley, Benjamin D. Walsh) suggested to import natural enemies from their homeland. It was C.V. Riley who organized the first intra state parasite transport in the USA: he sent parasitoids of the plum curculio (*Conotrachelus nenuphar*) to different localities in Missouri. Riley was alos the first to propose conservation of parasitoids of the rascal leafcrumpler of fruit trees (*Acrobasis indigenella*) by collecting larvae in their cases in mid-winter and then putting them away from the tree sufficiently far so that the larvae could not reach the trees anymore, but the parasites emerging from the parasitized ones could easily in the next spring. It was again Riley in 1873 who stimulated the first international transfer of an arthropod predator by sending the predatory mite *Tyroglyphus phylloxerae* to Europe for control of the grape phylloxera (*Daktulosphaira vitifolii*) to France. It established but did not result in effective control.

The first international shipment of a predatory insect took place in 1874, when aphid predators, among which *Coccinella undecimpunctata* were shipped from England to New Zealand. The ladybird beetle established. The first intercountry transfer of parasitic insects was that of *Trichogramma* from the USA to Canada in 1882. The first intercontinental parasitoid shipment took place in 1883, and was once more, organized by Riley: *Apanteles glomeratus* was sent from England to the USA for control of cabbage white butterflies and established. We will have to wait another 6 year before the spectacular success with *Rodolia* took place, again masterminded by Riley.

For more detailed reviews, see:

DeBach, P., ed. 1964. Biological Control of Insect Pests and Weeds. Cambridge Univ. Press, Cambridge: 844 pp.
DeBach, P., 1974. Biological Control by Natural Enemies. Cambridge University Press, Cambridge: 323 pp.

History of biological control in Latin America, the Neotropical Regional Section (IOBC-NTRS). After van Lenteren & Bueno, 2003. Augmentative biological control of arthropods in Latin America. BioControl 48: 123-139.

Although biological control has been practised in Latin America since the start of the 20th century, the written history of this field of science is limited, except for Chile (Rojas, 2005). Aspects of the history of biological control for Brazil can be found in Gomes (1962), for

Chile in Rojas (2005), and for Peru in Wille (1956). Hagen and Franz (1973) provided the first overview of biological control in South and Central America. A recent review on classical biological control in Latin America is given by Altieri and Nichols (1999). Until the 1970s the attempts to use natural enemies in South and Central America were scattered and uneven. The best known cases of biological control that have been implemented in several Latin American countries are (1) the introduction of *Rodolia cardinalis* for control of cottony cushion scale (*Icerya purchasi*), (2) the release of *Encarsia berlesi* for control of the white peach scale (*Pseudalacaspis pentagona*), and (3) the introduction of *Aphelinus mali* for control of woolly apple aphid (*Eriosoma lanigerum*), which have usually led to substantial or complete control. During the 1970s biocontrol activities intensified in Latin America as the result of the formation of departments of entomology and biological control.

Activities were very limited until the 1970s in Argentina, Brazil, Chile, Colombia, Ecuador, Uruguay and Venezuela (see table 2) and most programmes were based on classical (=inoculative) biological control. Peru was most active during this period (Wille, 1956). Augmentative releases were only used in British Guyana (Myers, 1935), and to a limited extent in Bolivia (Zapater, 1996) and Peru (Hagen & Franz, 1973).

Table 2. Application of biological control in Latin America in the period 1880 – 1970 (based on Hagen and Franz, 1973; van Lenteren & Bueno, 2003)

Country	Main pests for which biocontrol was developed	Inoculative	Augmentative
Argentina	white peach scale, woolly apple aphid, cottony cushion scale	+	-
Bolivia	frog hoppers in sugarcane, woolly apple aphid, cottony cushion scale sugar cane borers with *Telenomus*	+	+/-
Brazil	as in Argentina, and coffee berry borer, fruit fly, sugar cane borer	+	-
British Guyana	sugar cane borer with *Trichogramma* and *Telenomus*	+	+
Caribbean	sugar cane borer, cottony cushion scale	+	+
Chile	as in Argentina, and mealybugs	+	-
Colombia	woolly apple aphid, sugar cane borer	+	-
Costa Rica	citrus blackfly	+	-
Cuba	citrus blackfly	+	-
Ecuador	*Icerya montserratensis*	+	-
Mexico	citrus blackfly	+	-
Panama	citrus blackfly	+	-
Paraguay	unknown	?	?
Peru	as in Argentina, and scales on cotton, alfalfa aphid, sugar cane borer	+	+/-
Puerto Rico	mealybugs, cottony cushion scale, and other scale insects	+	-
Uruguay	as in Argentina	+	-
Venezuela	woolly apple aphid, cottony cushion scale, and sugar cane borer	+	-
Total number of countries with inoculative or augmentative control		16	4

Information about biocontrol in Central America and the Caribbean Islands is even more scattered than that of South America (Hagen & Franz, 1973). The best examples concern (1) complete biological control of the citrus blackfly, *Aleurocanthus woglumi*, as a result of inoculative releases with the parasitoid *Eretmocerus serius* and/or *Amitus hesperidum* in Cuba, Costa Rica, Mexico and Panama, (2) the use of tachinid and hymenopteran parasitoids (including inundative releases with *Trichogramma*) to control sugar cane borer on different Caribbean islands (Simmonds, 1958; Bennett & Hughes, 1959), and (3) control of several species of scales with coccinellids in Puerto Rico (Wolcott, 1958).

References:

Altieri, M.A. and Nichols, C.I., 1999. Classical biological control in Latin America. *In* "Handbook of Biological Control" (T.S. Bellows and T.W. Fisher, Eds.) pp. 975-991. Academic Press, San Diego.

Bennett, F.D., and Hughes, I.W., 1959. Biological control of insect pests in Bermuda. *Bull. Entomol. Res.* **50**, 423-436.

Gomes, J., 1962. Histórico do combate biológico no Brasil. *Boletim do Instituto de Ecologia e Experimentação Agricolas* 21, 89-97.

Hagen, K.S., and Franz, J.M., 1973. A history of biological control. In "History of Entomology" (R.F. Smith, T.E. Mittler, and C.N. Smith Eds.), pp. 433-476. Annual Reviews Inc., Palo Alto.

Lenteren, J.C. van, and Bueno, V.H.BP., 2003. Augmentative biological control of arthropods in Latin America. BioControl 48: 123-139.

Myers, J.C., 1935. Second report on an investigation into the biological control of West Indian insect pests. *Bull. Entomol. Res.* 26, 181-252.

Rojas, S., 2005. Control Biológico de Plagas en Chile: Historia y avances. Libros INIA 12, Ministry of Agriculture, Instituto de Investigaciones Agropecuarias, 125 pp.

Simmonds, F.J., 1958. Recent work on biological control in the British West Indies. Proceedings of International Congress of Entomology 10, 475-478.

Wille, J.E., 1958. El control biológico de los insectos agrícolas en el Perú. Proceedings International Congress of Entomology 10, 519-523.

Wolcott, G. N., 1958. The evanescence of perfect biological control. Proceedings of the International Congress of Entomology 10, 511-513.

Zapater, M.C. (Ed.) 1996. El Control Biológico en América Latina. IOBC, Buenos Aires

History of biological control in Europe, the West Palearctic Regional Section of IOBC (IOBC-WPRS). Based on Greathead (1976).

Development and application of biological control in Europe have been reviewed by Franz (1961a, b), Krieg & Franz (1989), Greathead (1976), Hagen & Franz (1973) and van Lenteren & Woets (1988). The initial practical demonstration of biological control in Europe was carried out in France in 1840: M. Boisgiraud released the carabid *Calosoma sycophanta* (L.) against the gypsy moth (*Lymantria dispar* (L.)) on poplars. At the same time in Germany, J.R.C. Ratzeburg moved heavily parasitized *Dendrolimus pini* (L.) into an outbreak area and recommended the use of ants (*Formica rufa* group) against forest defoliaters. The method of artificial colonization of forest ants has been studied extensively in the 20th century (for a review see Greathead, 1976). Also efforts to increase insectivorous birds by providing nesting facilities were popular in Europe, and the ant and bird work can said to be specific elements in the European pattern of biological control (Franz, 1961b). Conservation of natural enemies has been suggested in Europe as early as 1827 by G.L. Hartig. Many attempts to augment existing natural enemy populations have been made thereafter, often on a local sale. Most are inadequately documented and are, therefore, not treated in any detail here.

The earliest - unsuccessful - attempt to colonise a natural enemy in Europe was the importation of the acarid predator *Rhizoglyphus phylloxerae* (Riley & Planchon) in 1873 for control of the grape phylloxera *Viteus vitifolii* Fitch . The first success in use of exotic organisms dates from 1897 when the Portuguese imported and established the vedalia beetle *Rodolia cardinalis* (Mulsant) against the cottony cushion scale *Icerya purchasi* Mask. following its first appearance in Europe in the previous year. The labybird beetle was later introduced in other European countries and the success strongly stimulated interest in "classical" biological control. Several other coccinellids were introduced against a variety of pests, but these programs were less successful.

The first introduction of a parasitoid dates back to 1906 when Berlese imported *Prospaltella berlesi* (Howard) against mulberry scale *Pseudaulacaspis pentagona* (Targ.) (Berlese & Paoli, 1916). The failure of the 1926-1944 campaign to control the Colorado potato beetle *Leptinotarsa decemlineata* (Say) tempered the enthusiasm for biological control in Europe. Classical biological control has been relatively unsuccessful in Europe. The main reason for this is that few pests have been imported to Europe ("scarcity of obvious candidates").

Simmonds and Greathead (1977) estimate that more than 60% of the 200 insect pest species in the USA have been imported, whereas few arthropod pests were imported to Europe. However, the statement that biological control will be most successful in situations where natural enemies are imported from abroad, against pests which were also imported, is a dogma unnecessarily hampering developments and not longer tenable. During the past decades, for it has been shown that all combinations of exotic and native natural enemies and pests are worth trying (e.g. table 2 in van Lenteren et al., 1987).

One notable exception to a number of failures to employ exotic natural enemies against exotic pests was Speyer's success in using the parasitoid *Encarsia formosa* Gahan for control of *Trialeurodes vaporariorum* (Westwood) in greenhouses (Speyer, 1927). This parasitoid is still commercially used on a large scale, and forms the focal point in integrated pest management (IPM) programs for greenhouses (van Lenteren & Woets, 1988). The use of native natural enemies for biological control during the first part of the 20th century has been summarized by Sachtleben (1941). Greathead (1976) has updated that summary. Since Greathead's (1976) review a number of native natural enemies has been evaluated and selected for biological control and these are now commercially used (van Lenteren et al., 1987; van Lenteren, 2003).

Interest in biological control lessened with the appearance of the synthetic pesticides after 1940, but the development of resistance and the recognition of unwanted side-effects during the 1950's revived interest in biological control, and led to the formation of the International Organisation for Biological Control (IOBC) in 1955 (now the Western Palaearctic Regional Section of the IOBC). This European section of the IOBC has been the driving force behind a change of thinking in crop protection since, and coordinated many cooperative biological control projects (van Lenteren et al., 1992; and see www.IOBC-WPRS.org).

Inundative types of biological control were first taken up in Russia in 1913 with the mass rearing and periodic releases of *Trichogramma* spp. *Trichogramma* spp. have not been used in inundative programs on a large scale in West and South Europe, but presently *Trichogramma* is commercially applied. This work has been reviewed by Schieferdekker (1970). The first experiments date from the 1920's (Voelkel, 1925). Most of the inundative releases were discontinued and rated unsuccessful (Greathead, 1976). Presently one project with *Trichogramma* seems commercially successful, that of the control of *Ostrinia nubilalis* with *Trichogramma evanescens*. Inundative releases have also figured in the attempt at biological control of the olive fly *Dacus oleae* (Gmel.)) by *Opius concolor* Szépl. (Liotta & Mineo, 1968). In Italy the *O. concolor* was successfully used during the 1960's. The most important developments of augmentative releases in West Europe have been in greenhouses (van Lenteren & Woets, 1988; van Lenteren, 2000).

Europe has served as important source for export of natural enemies for more than a century, principally to the USA and Canada (Clausen, 1978, Greathead, 1976). Collection and exportation of natural enemies has been the area of activity of the Commonwealth Agricultural Bureau's International Institute of Biological Control (CIBC; now CABI), the European Parasite Laboratory of the USDA-USA and the Commonwealth Scientific and Industrial Research Organization (CSIRO) Australia, but many European countries contributed to the search and shipment of natural enemies.

In this section, the European developments of microbial control are not summarized, but see Steinhaus (1956) and Zimmermann (1986) for reviews.

References

Berlese, A., Paoli, G., 1916. Un endofago esotico efficace contro il Chrysomphalus dictyospermi Morg. Redia 11: 305-307.

Clausen, C.P. ed. 1978. Introduced Parasites and Predators of Arthropod Pests and Weeds: a World Review. USDA/ARS, Agricultural Handbook No. 480, Washington: 545 pp.

Franz, J.M., 1961a. Biological control of pest insects in Europe. Annual Review of Entomology 6: 183-200.

Franz, J.M., 1961b. Biologische Schaedlingsbekaempfung. In: Handbuch der Pflanzenkrankheiten. Ed. P. Sorauer. Paul Parey, Berlin. Vol. 6: 1-302.

Greathead, D.J., 1976. A Review of Biological Control in Western and Southern Europe. CAB, Farnham Royal: 182 pp.

Hagen, K.S., and Franz, J.M., 1973. A history of biological control. In “History of Entomology” (R.F. Smith, T.E. Mittler, and C.N. Smith Eds.), pp. 433-476. Annual Reviews Inc., Palo Alto.

Krieg, A. & J.M. Franz 1989. Biologische Schaedlingsbekaempfung. Parey, Hamburg: 302 pp. Lenteren, J.C. van, 2000. A greenhouse without pesticides: fact of fantasy? Crop Protection 19:375-384.

Lenteren, J.C. van (ed.), 2003. Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. CABI Publishing, Wallingford, UK: 327 pp.

Lenteren, J.C. van, A.K. Minks & O.M.B. de Ponti, eds., 1992. Biological Control and Integrated Crop Protection: towards environmentally safer agriculture. Pudoc, Wageningen: 239 pp.

Lenteren, J.C. van & J. Woets, 1988. Biological and Integrated Pest Control in Greenhouses. Annual Review of Entomology 33: 239-269.

Lenteren, J.C. van, J. Woets, P. Grijpma, S.A. Ulenberg & O.P.J.M. Minkenberg, 1987. Invasions of pest and beneficial insects in the Netherlands. Proceedings Royal Dutch Academy of Sciences, Ser. C. 90: 51-58.

Liotta, G., Mineo, G., 1968. Lotta biologica artificiale contro la mosca delle olive a mezzo dell' *Opius concolor siculus* Mon. in Sicilia nel 1968. Boll. Ist. Ent. Agr. Palermo 7: 183-196.

Sachtleben, H., 1941. Biologische Bekaempfungsmassnahmen. In: Handbuch der Pflanzenkrankeiten. Ed. P. Sorauer. Paul Parey, Berlin 6 (2): 1-120.

Schieferdecker, H., 1970. Zum Stand der *Trichogramma*-Forschung in Europa und deren weitere Aufgaben. Tag. Ber. Dt. Akad. Lanbw. Wiss. Berlin No. 110: 137-175.

Simmonds, F.J., Greathead, D.J., 1977. Introductions and pests and weed problems. In: Origins of pest, parasite, diseases and weed problems. J.M. Cherrett & G.R. Sager. Blackwell, Oxford: 109-124.

Speyer, E.R., 1927. An important parasite of the greenhouse white-fly (*Trialeurodes vaporariorum* Westwood). Bull. Entomol. Res. 17: 301-308.

Steinhaus, E.A., 1956. Microbial control – the emergence of an idea. A brief history of insect pathology through the nineteenth century. Hilgardia 26: 107-160.

Voelkel, H., 1925. Ueber die praktische Bedeutung der Schlupfwespe *Trichogramma evanescens* Westw. Arb. Biol. Bund. Anst. Ld.- U. Forstw. 14: 97-108.

Zimmermann, G., 1986. Insect pathogenic fungi as pest control agents. In: Biological Plant and Health Protection. J.M. Franz, ed. Fischer Verlag, Stuttgart: 217-231.

History of IOBC

A book about the history and future of IOBC has been published recently: Boller, E.F, J.C. van Lenteren and V. Delucchi (eds.) 2006. International Organization for Biological Control of Noxious Animals and Plants: History of the first 50 Years (1956-2006). IOBC, Zürich, 287 pp. The book can be obtained by sending 10 Euro or 15 US Dollars in an enveloppe to Prof.dr. J.C. van Lenteren, Laboratory of Entomology, Wageningen University, POBox 8031, 6700 EH, Wageningen, The Netherlands

The first official plenary session of IOBC took place on 20 November 1956 in Antibes, France, after ideas had been expressed to establish an international organization of biological control at the 8th International Congress of Entomology in 1948 in Stockholm, where experts in this field met under the auspices of and supported by the International Union of Biological Sciences (IUBS). At that time, ecologists and entomologists had serious concerns about environmental and health effects of chemical pest control, and they considered biological control an important potential alternative for pesticides. Biological control was, of course, not new to science. The reason that IOBC originally developed in Europe and was limited to that area for its first 25 years of existence, was due mainly to the lack of a coordinating organization for biological control in this area. Other areas, like northern America and the British Commonwealth (including Australia and New Zealand), had strong organizations and a long standing history in the field of biological control. Still it was felt necessary by many biological control researchers to form a truly worldwide organization that would overview and coordinate the activities of this environmentally safe method of pest, disease and weed management. The formation of IOBC Global encountered some early diplomatic difficulties when another organization, the International Advisory Committee for Biological Control (IACBC), also claimed worldwide leadership in biological control. It was the International Union of Biological Sciences (IUBS) which took the initiative to assist in trying to solve this problem. Under the leadership of F. Stafleu, Secretary General of International Union of Biological Sciences, an agreement was finally reached at a historic meeting between IOBC, IACBC and IUBS held from 17-19 November 1969 at Amsterdam, The Netherlands. At the end of the meeting participants did, among others, agree that the name of the new organisation should be IOBC = International Organization for Biological Control. In 1971, IOBC Global was established.

The formation of numerous working groups resulted in excellent work and several important biological control and integrated pest management (IPM) projects, and later integrated plant protection (IPP) projects were developed and implemented. The activities of the various Regional Sections have evolved differently, but experiences in certain regions have helped developments in other regions. With its global network of collaborating scientists, IOBC now has the status of a dependable, professional organisation providing objective information about biological control and IPM. We expect that the IOBC will continue to play an important role in realizing sustainable and environmentally friendly food production worldwide.

Contents IOBC History of the first 50 years

INTERNATIONAL ORGANIZATION
for BIOLOGICAL CONTROL
of Noxious Animals and Plants
The IOBC promotes the development of biological control and its application in integrated plant protection and production programmes. Biological control is the use of living organisms to prevent the losses caused by pest organisms or, more succinctly, the use of biota to control biota. The IOBC coordinates biological control activities worldwide in six regional sections (Africa, Asia and the Pacific, East Europe, West Europe and the Mediterranean, North America, and Central, Caribbean and South America) and working groups. This book describes the origin and development of the organisation and gives a historical overview of its activities.
50 Years IOBC 1956-2006
50 Years IOBC
History of the first 50 Years (1956-2006)
Ernst F. Boller, Joop C. van Lenteren & Vittorio Delucchi (Editors)

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5. Current situation of biological control (including region/country revieuws)

Introduction

In this chapter, we aim to summarize the current situation with regard to biological control world wide. However, it is often difficult to obtain reliable data about areas under different forms of biological control. Particularly, information about inoculative (classical) biological control is hard to get. Anyone who has this kind of information is kindly asked to send this to the editor of this book, who will then include it in this chapter.

Natural biological control

Natural (biological) control is constantly active in all world terrestrial ecosystems on 89.5 million km^2. Most of the potential arthropod pests (95%, 100,000 arthropod species) are under natural (biological) control; all other control methods used today are targeted at the remaining 5,000 arthropod pest species.

Current use of inoculative (classical) biological control

Inoculative or classical biological is the regulation of an exotic pest by exotic natural enemies. Classical refers to the spectacular early successes in pest control by using exotic natural enemies such as the cottony cushion scale, *Icerya purchasi* in California with the predatory coccinelled *Rodolia cardinalis* imported from Australia in 1888 (Caltagirone, 1981). This specatular success was followed by that of biological control of a weed, the prickly pear (*Opuntia* spp.), in Australia with the pyralid *Cactoblastus cactorum* imported from Argentina in the 1920s, and many other successes. Comprehensive world reviews of classical biological control cases can be found in DeBach (1964), Clausen (1978; this review illustrates, among others, that natural enemies had been imported against 294 species of arthropod pests and weeds by 1978), Laing & Hamai (1976) and Bellows & Fisher (1999). An early history of biological control was written by Doutt (1964). Caltagirone (1981) provides details of 12 successful classical biological control programmes that were developed in the period 1950-1980. Caltagirone & Doutt (1989) extensively describe the earliest classical biological control success, that of the control of cottony cushion scale: it is an unparralleled history in the annals of entomology for its drama, human interest, political ramifications, and significance.

Classical biological control is estimated to be applied on 3.5 million km^2 (350 million hectares), which is about 8% of land under culture, and has very high benefit-cost ratios of 20-500 : 1

Table **. Worldwide use of major inoculative (classical) biological control programmes (after *)**

Natural enemy	Pest and crop	Area under control (in hectares)
Rodolia cardinalis	Cottony cushion scale from 1888 onwards USA Europe	
Cactoblastus cactorum	Prickly pear from 1920** onwards Australia	

References

Bellows, T.S & T.W. Fisher, eds., 1999. Handbook of Biological Control. Academic Press, San Diego: 1046 pp

Caltagirone, L.E., 1981. Landmark examples in classical biological control. Annu. Rev. Entomol. 26: 213-232.

Caltagirone, L.E. & Doutt, R.L., 1989. The history of the Vedalia beetle importation to California and its impact on the development of biological control. Annu. Rev. Entomol. 34: 1-16.

Clausen, C.P., ed., 1978. Introduced parasites and predators of arthropod pests and weeds. USDA Handbook 480, 545 pp.

DeBach, P., ed., 1964. Biological control of insect pests and weeds. Cambridge, UK: 844 pp.

Doutt, R.L., 1964. The historical development of biological control. In: Biological control of insect pests and weeds, P. DeBach, ed. Cambridge, UK: pp. 21-42.

Laing, J.E. & Hamai, J., 1976. Biological control of insect pests and weeds by imported parasites, predators and pathogens. In: Theory and practice of biological control, C.B. Huffaker & P.S. Messenger, eds. Academic Press, New York: pp. 685-743.

Current use of augmentative biological control (based on van Lenteren & Bueno, 2003).
Augmentative biological control is applied worldwide, and more than 150 species of natural enemies are now commercially available for augmentative biological control (see table with a list of these species elsewhere in this internet book). Data on current use of augmentation are very hard to obtain and, thus, the estimates given below are incomplete. The latest comprehensive worldwide review dates from 1977 (Ridgway and Vinson, 1977), which provides data about the use of natural enemies in the USSR (on 10 million hectares), China (1 million hectares), West Europe (< 30,000 hectares), and North America (<15,000 hectares). Since the time of that review, more than 100 new species of natural enemies have become available and are commercially produced or mass reared by governmental institutes (van Lenteren, 1997, van Lenteren, 2003). An overview of the most important applications of augmentative biological control is given in the table.

Concerning the use of egg parasitoids, the former USSR ranked first in application of *Trichogramma* (> 10 million hectares; Filoppov, 1989), followed by China (all crops: 2.1 million hectares; Li, 1994; 2 million hectares of the Asian cornborer, *Ostrinia furnacalis* Guenée with *Trichogramma dendrolini* Matsumura in 2004; Wang et al., 2005) and Mexico (1.5 million hectares; Dominguez, 1996). The former USSR claimed to have treated more than 25 million hectares annually with *Trichogramma* in the 1980s (Filoppov, 1989 and personal communication), but others have questioned the way in which these areas were calculated: it seems that fields which had received for example three treatments of *Trichogramma*, were included three times in the estimates. Therefore, the area under biological control in the previous USSR was reestimated as maximally 10 million hectares. Application with *Trichogramma* in Japan, South East Asia, South America, USA, Canada and Europe is limited because of economic reasons (high labour costs involved in mass production) and more intensive use of pesticides that have a negative effect on natural enemies. Estimates of applications with *Trichogramma* in all other countries with the exception of the former USSR, China and Mexico are in the order of 1.5 million hectares. Inundative releases of *Trichogramma* for control of lepidoptorous pests are being studied in more than 50 countries. Other egg parasitoids, like *Trissolcus basalis*, are used on much smaller areas (see table 1).

Also, natural enemies attacking larval and pupal stages are not used to a large extent in augmentative biological control in field crops, with the exception of the use of *Cotesia* parasitoids against sugarcane borers in Brazil and several other Latin American countries. In Brazil 23.6 million cocoon masses of *C. flavipes* and 1.5 million adults of the tachinid fly *Paratheresia claripalpis* Wulp. were released over an area of 200,000 hectares of sugar cane in 1996 (Macedo, 2000).

Microbial biocontrol agents such as nematodes, fungi, bacteria and viruses are applied on more than 1.5 million hectares to control soil dwelling pests (Federici, 1999; Jackson *et* *al.*, 2000) and above-ground pests (Federici, 1999; Gelernter & Lomer, 2000). The largest area under treatment with microbials seems to be that of soybean where *Anticarsia gemmatalis* Hübner caterpillars are controlled with its nucleopolyhedrovirus (AgMNPV) on 1 million hectares, but also Russia (1 million hectares) and Cuba have large areas treated with microbials (table 1).

Greenhouse pests are currently managed through biological control on 5% of the about 300,000 hectares of protected cultivation worldwide (van Lenteren, 2000). Although this is a relatively small surface, it is one of the main areas for commercial production and release of natural enemies. The large number of natural enemies presently available, often with several species for each pest, has made greenhouse biological control programmes stable and reliable (Albajes *et al.*, 1999).

Worldwide, there are about 85 commercial producers of natural enemies for augmentative forms of biological control: 25 in Europe, 20 in North America, 6 in Australia and New Zealand, 5 in South Africa, about 15 in Asia (Japan, Korea, India etc.), and about 15 in Latin America. The worldwide turnover of natural enemies of all producers was estimated to be 25 million US$ in 1997, and about 50 million US$ in 2000, with an annual growth of 15-20% in subsequent years (Bolckmans, 1999, and personal communication). Currently, more than 75% of all activities in commercial augmentative biocontrol (expressed in monetary value) take place in North Europe and North America. Emerging markets are those of Latin America, South Africa, Mediterranean Europe, and China, Japan and Korea in Asia. In addition to the commercial producers, there are many natural enemy production units funded by the government, such as in Brazil (40 facilities), China (many, number unknown), Colombia (more than 20 facilities), Cuba (more than 200 facilities), Mexico (30 facilities) and Peru (more than 20 facilities) (for references the section on current situation of biological control in Latin America, for China see Li, 1994).

Currently, augmentative forms of biological control are applied on up to 17 million hectares (see table 1).

Table 1. Worldwide use of major augmentative biological control programmes (after van Lenteren, 2000. Measures of Success in Biological Control Of Arthropods By Augmentation Of Natural Enemies. In: Measures of Success in Biological Control, G. Gurr & S. Wratten (eds.). Kluwer Academic Publishers, Dordrecht: 77-103)

Natural enemy	Pest and crop	Area under control (in hectares)
Trichogramma spp.	Lepidopteran pests in vegetables, cereals, cotton	3-10 million, Russia
Trichogramma spp.	Lepidopteran pests in various crops, forests	> 2 million, China
Trichogramma spp.	Lepidopteran pests in corn, cotton, sugarcane, tobacco	1.5 million, Mexico
Trichogramma spp.	Lepidopteran pests in cereals, cotton, sugarcane, pastures	1.2 million, S. America
AgMNPV	Soybean caterpillar in soybean	1 million, Brazil
Entomopathogenic fungi	Coffee berry borer in coffee	0.55 million, Colombia
Microbial agents	Lepidopteran pests and others	1 million, Russia 2004
Cotesia spp.	Sugarcane borers	0.4 million, S. America, China
Trichogramma spp.	Lepidopteran pests in cereals and rice	0.3 million, SE Asia
>30 spp. of nat. enemies	Many pests in greenhouses and interior plant scapes	0.05 million, worldwide
Trichogramma spp.	*Ostrinia nubilalis* in corn	0.05 million, Europe
Egg parasitoids	Soybean stink bugs in soybean	0.03 million, S. America
Orgilus sp.	Pine shooth moth, pine plantations	0.05 million, Chile
5 spp. of nat. enemies	Lepidoptera, Homoptera, spider mites in orchards	0.03 million, Europe

Situation for regions/countries (to be written)

Current situation of biological control in Neotropical Regional Section (IOBC-EPRS)

To be written

Russia

M.V. Shternshis, 2004. Ecologically safe control of insect pest: the past, the present and the future. In: Emerging concepts in plant health management, R.T. Lartey & A. Caesar, eds. Research Signpost, Kerala, India, 187-212. ISBN: 81-7736-227-5. The review article by Dr. Margarita Shternshis focuses on the most widespread micribial control agents used in Russia: Bacillus thuringiensis, baculoviruses, entomopathogenic fungi and some microbial metabolites. Special attention is given to the enhancement of the insecticidal activity and relevant formulations. Dr. Shternshis estimates that in 2004 at least 1 million of hectares are treated with microbials in Russia, while it were 3 million hectares before 1989 (pers. comm. Shternshis, 2005).

Macrobials, *mainly Trichogramma*, are estimated to be used on 3 million hectares in 2004, while it were >10 million hectares before 1989 (pers. com. Sadomov, 2005).

Current situation of biological control in Neotropical Regional Section (IOBC-NTRS). After van Lenteren and Bueno, 2003. Augmentative biological control of arthropods in Latin America. BioControl 48: 123-139.

Information about current use of biological control in Latin America as given in the table 2 was compiled from Altieri & Nichols (1999; only classical biocontrol), Zapater (1996), various papers cited below, and from personal communications with M. Gerding (Chile), R. de Vis (Colombia), A.L. Valido (Cuba), L.A.R. del Bosque (Mexico), and G. Gonzalez (Panama). Below the situation for augmentative biological control is summarized per country.

Table 2. Present situation of biological control in Latin America (after van Lenteren & Bueno, 2003. Augmentative biological control of arthropods in Latin America. BioControl 48: 123-139).

Country	Main pests for which biocontrol was developed	Inoculative	Augmentative (hectares)
Argentina	very limited: sugar cane borer with *Trichogramma*	+	+/- (<100)
Bolivia	very limited: sugar cane borer with egg parasitoids and tachinids	+/-	+/- (?)
Brazil	sugar cane borer with parasitoids, soybean caterpillar with AgNPVirus, soybean bugs with parasitoids, *Sirex* woodwasp with nematodes	+	+(1,320,000)
Chile	pine shoot moth with *Orgilus obscurator*, house flies with parasitoids, many other augmentative programmes in development	+	+ (50,000)
Colombia	cotton, soybean, sorghum and suger cane pests with *Trichogramma* and other parasitoids, house flies with parasitoids, many different pests with entopmopathogens in various crops	+	+ (800,000)
Costa Rica	cotton and sugar cane pests with *Trichogramma, Cotesia* and *Metharizium*	+	+(thousands)
Cuba	sugar cane borer with *Lixophaga diatraea*, *Panonychus citri* with *Phytoseiulus macropilis,* Lepidoptera with *Trichogramma*	+	+(700,000)
Ecuador	sugar cane and corn with local *Trichogramma*, coffee berry borer	+	+ (?)
Guatemala	pests in cotton and vegetables with *Trichogramma*, and baculovirus	+/-	+ (20,000)
Honduras	vegetable and sugar cane pests with *Diadegma* and *Cotesia*, resp.	+/-	+/- (?)
Mexico	corn, soybean, sugar cane, citrus pests with *Trichogramma* and others	+	+(1,500,000)
Nicaragua	classical biocontrol, corn, cotton, soybean pests with *Trichogramma*	+	+/- (?)
Panama	sugar cane borer with *Cotesia flavipes*	+	+(4,500)
Paraguay	soybean caterpillar with AgNPVirus	?	+ (100,000)
Peru	sugar cane, rice and corn pests (*Trichogramma, Telenomus*), pests in citrus (local *Aphytis*), pests in olive (*Methaphycus*) and others	+	+ (>1,300)
Uruguay	sugar cane borer with *Trichogramma*	+	+/- (<100)
Venezuela	corn army worm with *Telenomus*	+	+ (4,300)
Total number of countries with inoculative or augmentative control		16	17

Argentina
In Argentina augmentative biological control is considered with enthusiasm, although application is still limited (Basso & Morey, 1991; Zapater, 1996).

Bolivia
In Bolivia augmentative biological control is considered with enthusiasm, although application is still limited (Basso & Morey, 1991; Zapater, 1996).

Brazil
Besides classical biological control (several programmes, the most recent one concerns control of *Sirex* wood wasp with entomopathogenic nematodes and 3 parasitoids; Iede & Penteado, 1998). Brazil is very active in augmentative biological control with about 44 mass production facilities. Brazil applies *Cotesia* against sugar cane borer on about 300,000 hectares (Macedo, 2000, and Arigoni, personal communication), AgNPVirus against soybean caterpillar on more than 1,000,000 hectares (Moscardi, 1999), egg parasitoids of soybean bugs on 20,000 hectares (Corrêa-Ferreira, personal comunication), the egg parasitoid *Trihcogramma pretiosum* is released in an area of about 2,600 hectares of open field tomatoes against *Tuta absoluta* (N. Hiji, personal communication), and the predatory mite *Neoseiulus californicus* against the spider mite *Panonychus ulmi* in apple orchards on about 1,800 hectares (Monteiro, personal communication). Biological control of pests in greenhouses is now under development (Bueno, 1999).

Chile
In Chile, many new activities took place since 1970 (Rojas, 2005). A large augmentative project is running on control of *Rhyacionia buoliana* (pine shoot moth) with the parasitoids *Orgilus obscurator* (50,000 ha) and *Trichogramma nerudai* (200 ha, experimental). Other experimental programmes concern greenhouse tomatoes, where whitefly (*Trialeurodes vaporariorum*) is controlled with several *Encarsia* and *Eretmocerus* species, and the leafmining caterpillar *Tuta absoluta* with *Trichogramma nerudai*. Further, flies in poultry and other livestock are controlled by periodic releases of *Muscidifurax raptor* and *Spalangia endius* since 1990. Many other pests are under study for biological control with entomopathogens (all Chilean information based on M. Gerding, personal communication).

Colombia
In Colombia, augmentative biological control is intensively applied in the Valle del Cauca, where about 200,000 ha cultivated with cotton, soybean, cassava, tomato, sorghum and sugercane receive periodic releases of *Trichogramma*. The use of *Trichogramma* in cotton has recently sharply decreased because of the occurrence of *Anthonomis grandis* at the end of the 1980s. In 1991 *Trichogramma* was still applied on 30,000 ha of cotton, now the parasitoids are only used on 5,000 ha. The use of biocontrol in sugar cane has increased recently. Three parasitoids (*Trichogramma exiguum*, *Metagonistylum minense* and *Pharatheresia claripalpis*) are introduced to control the sugarcane borer (*Diatraea saccharalis*) and other caterpillars on about 130,000 ha. Flies in poultry and other livestock are controlled on a large scale by periodic releases of *Muscidifurax* and *Pachycrepoideus*. Also, Lepidoptera are under augmentative biological control on large areas of forest. Colombia has been working on the mass production technology of parasitoids, predators and entomopathogens (Garcia, 1996), and had 30 mass production facilities for macrobial biocontrol agents in 1990, a number that has decreased to 9 producers in 2000. Colombia seems to have brought *Trichogramma* to South America at the end of the 1970s, and from

there its application has spread to Costa Rica, Venezuela, Paraguay, Ecuador and Brazil. Colombia is well known for its research an application on entomopathogenic fungi such as *Beauveria bassiana*, *Verticillium lecanii*, *Metarhizium anisopliae* and *Paecilomyces fumosoroseus*. The largest applications concern (1) the spraying of *Beauveria bassiana* and *Metarhizium anisopliae* on 550,000 ha of coffee against the coffee berry borer (*Hypothenemus hampei*) and (2) the application of *Beauveria bassiana* against *Opsiphanes cassina* on 130,000 ha of oil palm, but the entomopathogens are also used for control of *Anthonomus grandis* in cotton, thrips in ornamentals, whiteflies in beans and tomatoes, grasshoppers in pastures and insect pests in rice and citrus. Currently, Colombia has 5 producers of entomopathogenic fungi. The National Center for Coffee Research (CENICAFE) is doing extensive research on the imported parasitoids *Cephalonomia stephanoderis* and *Prorops nasuta* of the coffee berry borer. These parasitoids are now mass reared and released in coffee fields (Bustillo et al., 1995). Colombia has several integrated control programmes for greenhouse pests (see below; de Vis, 1999)

Costa Rica
Costa Rica uses *Trichogramma* to control pests in cotton and sugarcane (Hernandez, 1996).

Cuba
Cuba has shown many activities in the field of augmentative releases. *Trichogramma* species are applied more than 685,000 ha for control of Lepidoptera in pastures, cassava and vegetables (A.L. Valido, personal communication). Sugar cane borers are controlled with the native tachinid parasitoid *Lixophaga diatraea*, and the spider mite *Panonychus citri* with the predatory mite *Phytoseiulus macropilis* (areas unknown but large; Aleman et al., 1998). Further, the use of insect pathogenic fungi is particularly impressive, with an area of 516,895 ha treated in 1995 (Altieri and Pinto, 1975). An interesting programme concerns the control of the sweet potato weevil (*Cylas formicarius*) in more than 15,000 ha with predators (*Pheidole megacephala* ants) and entomopathogenic nematodes (*Heterorhabditis* spp.) (A.L. Valido, personal communication). Cuba has more than 220 centers for the production of entomophages and entomopathogens (Altieri & Nichols, 1999), where large amounts of insect pathogenic fungi and *Bacillus thuringiensis*, as well as *Trichogramma* spp. and sugar cane borer parasitoids are produced. Based on the information we had available, we estimate that currently a total area of 700,000 ha is under biological control in Cuba, because the predators and parasitoids (used on 700,000 ha) are released in the same crops as where the pathogens (used on more than 500,000 ha) are applied.

Ecuador
Ecuador has recently started with augmentative control of pests in sugar cane and corn using local species of *Trichogramma* (Klein Koch, 1996). Further, there is some integrated control and biological control of pests in roses (about 10 ha), and natural control of leafminers in ornamentals in the field (about 50 ha).

Guatemala
Guatemala is using *Trichogramma* against pests in cotton (14,000 ha), and a baculovirus against pests in vegetables and cotton (3,500 ha).

Honduras
In Honduras augmentative biological control is considered with enthusiasm, although application is still limited (Basso & Morey, 1991; Zapater, 1996).

Mexico

Mexico has been very active in developing augmentative control during the past 30 years. Many species of natural enemies (parasitoids, predators and pathogens) are mass produced in the more than 30 centers for rearing of beneficial insects. Augmentative releases with *Trichogramma*, and other parasitoids, predators and pathogens are made in crops like corn, cotton, sugar cane, sunflower, coffee, tobacco, soybean, sorghum, vegetables, ornamentals, bean, wheat, citrus and forests on 1,500,000 ha annually (Dominguez, 1996). Some examples about augmentative releases by one organization (Centro Nacional de Referencia de Control Biologico) in their five production centres (Centros Regionales de Estudios y Reproduccion de Insectos Beneficos) in 1998 are: *Trichogramma* releases on more than 640,000 ha, *Chrysoperla* on more than 100,000 ha, *Habrobracon* on more than 45,000 ha and entomopathogenic fungi on more than 6,000 ha (H.C.A. Bernal & L.A.R. del Bosque, personal communication). In addition to natural enemy production by these centres, commercial sugar mills and other companies are also producing biocontrol agents like *Trichogramma* for at least another 100,000 ha and entomopathogenic fungi for more than 50,000 ha (H.C.A. Bernal & L.A.R. del Bosque, personal communication).

Nicaragua

In Nicaragua augmentative biological control is considered with enthusiasm, although application is still limited (Basso & Morey, 1991; Zapater, 1996).

Panama

Panama is using *Cotesia flavipes* for control of sugar cane borers in sugarcane on about 4500 ha.

Peru

Historically, Peru mainly worked on classical biological control and has imported more than 100 species of biological control agents since 1904. Augmentative programmes have been developed recently for control of pests in, among others, asparagus, sugar cane, rice and corn (*Trichogramma*, *Telenomus*), pests in citrus (local *Aphytis*), pests in olive (*Methaphycus*, *Coccophagus*, *Chrysoperla*), and pests in potato (*Copidosoma*), tomato (*Paecilomyces* spp.), coffee and forests (*Beauveria*). Peru currently has 82 mass rearing facilities for natural enemies and 27 laboratories for production of entomopathogens (Beingolea, 1996; Programa Nacional de Control Biologico del Servicio Nacional de Sanidad Agraria (SENASA), information leaflet, 2000). In these 109 facilities 27 species of biological control agents are mass produced. In the 1970s the national insectary for introduction and rearing of beneficial insects reared *Trichogramma* spp. for releases on about 1,300 ha (Altieri & Nichols, 1999). Peru aims to apply biological pest control on about 240,000 ha within the coming 5 years (SENASA, inormation leaflet, 2000).

Uruguay

In Uraguay augmentative biological control is considered with enthusiasm, although application is still limited (Basso & Morey, 1991; Zapater, 1996).

Venezuela

Venezuela is using *Telenomus remus* against *Spodoptera frugiperda* in corn (Ferrer, 1998).

Current situation of biological and integrated control in Western Palearctic Regional Section (IOBC-WPRS).

Although IOBC-WPRS is one of the most active regions, has many working groups and publishes 10-15 bulletins annually with proceedings of meetings, the area under biological and integrated pest management is not documented very well, with the exception of augmentative releases in greenhouses, maize, orchards and vineyards.

Where is biological control and IPM used in Europe?

Until 1950 integrated pest management was not recognized as such but the main elements were already in use for centuries. Organic pesticides were hardly available before that period and many different control techniques were combined. Cultural control, host plant resistance and biological control were important aspects of the overall activities to reduce pests and diseases. Interest in integrated control developed shortly after the appearance of the synthetic pesticides after 1940, because of the development of resistance and the recognition of unwanted side-effects (see chapter on IPM).

In Europe, IPM programmes are commercially applied currently in different crops (see table 3 and 4, extracted from van Lenteren et al., 1992 and van Lenteren 1993). Some programmes are better characterized as guided or supervised control than with the term IPM, e.g. field vegetables, cereals and several orchard control procedures, because the difference with conservative chemical control lays only in the application of spray thresholds instead of applying calender or preventive sprays. Others are based on one or a few biological control components, e.g. vineyards and mais. Finally there is a category contain many different elements of IPM, like the orchard and greenhouse programmes. All programmes summarized in the table result in considerable reductions in use of chemical pesticides (20 - 99%) and several IPM procedures are applied on significant areas.

The first overview of biological control in Europe that appeared after the van Lenteren (1993) review is the one by Sigsgaard (2006) in which all open field applications of augmentative biological control are discussed, and all natural enemies that are currently in use are listed. Sigsgaard's overview shows that the area under biological control only increased a little since the 1990s.

The successful IPM programmes in West Europe have a number of characteristics in common, such as:

1. Their use was promoted only after a complete IPM programme had been developed covering all aspects of pest and disease control for a crop
2. An intensive support of the IPM programme by the advisory/extension service was necessary during the first years
3. The total costs of crop protection in the IPM programme were not higher than in the chemical control programme
4. Non-chemical control agents (like natural enemies, resistant plant material) had to be as easily available, as reliable, as constant in quality and as well guided as chemical agents.

Table 3. Guided and integrated control programmes applied in Europe (after van Lenteren et al., 1992 and van Lenteren, 1993)

Crop	Type	Elements	Area under IPM in Europe/ Reduction in pesticides
field vegetables	guided	monitoring - sampling - warning host-plant resistance diseases/pests	5% of total area 20-80% reduction
cereals	guided	monitoring - sampling - forecasting host-plant resistance diseases	10% of total area 20-50% reduction
maize	integrated	mechanical weeding - host-plant resistance diseases - biocontrol of insects	4% of total area 30-50% reduction
vineyards	integrated	biocontrol of mites - host-plant resistance	20% of total area

		diseases, pheromone mating disruption	30-50% reduction
olives	integrated	cultural control - biocontrol insects host-plant resistance diseases/pests monitoring - sampling - pheromones	very limited
orchards apple/pear	guided	monitoring-sampling selective pesticides	15% of total area 30% reduction
	integrated	monitoring - sampling – pheromones biocontrol - selective pesticides host-plant resistance diseases	7% of total area 50% reduction
greenhouse vegetables	integrated	monitoring - sampling - biocontrol pests and diseases, host-plant resistance diseases	30% of total area 50-99% reduction

Table 4. Most important augmentative biological control programmes in Europe (these programmes are included in the above table, and are completed with data from Sisgaard, 2006)

Crop	Pest	Natural enemy	Area under biological control in hectares/ Ref	
maize	*Ostrinia nubilalis*	*Trichogramma brassicae*	100,000 /	van Lenteren et al., 1992; Smith, 1996; Sigsgaard, 2006
orchards apple /pear	various	various	30,000 /	Blommers, 1994; van Lenteren et al., 1992; Sigsgaard, 2006
greenhouses	many	many	50,000 /	van Lenteren, 2000 Zheng et al. 2005
strawberries	*Tetranychus urticae*	*Phytoseiulus persimilis*	< 20,000 /	Sigsgaard, 2006
vineyards	*Tetranychus urticae*	*Typhlodromus pyri* *Amblyseius andersoni*	40,000 /	van Lenteren et al., 1992; Sigsgaard, 2006

Numbers of researchers working on biological control

Table 5. Estimated numbers of biological control researchers per country/region

Country/region	Biocontrol research public	private	Entomologists	Source
Argentina	20	2		M. Zapater, 2006
Brazil	300	15		R.Parra, 2005
Canada	200			J.L. Schwartz, 2005
Chile	30	10	100	M. Gerding, F. Rodriguez, 2005
China			> 8,000	Qin Jun-de, 1992
Japan	100	20	1,100	XVI Int Congr Entomol. 1980 Yano pers com 2005
Mexico	225			Biocontrol site Mexico
Netherlands	50	30	200	J.C. van Lenteren, 2005
South Africa	45			R. Kfir, 2004
Uruguay	5		15	C. Basso pers com 2006

References

Albajes, R., Gullino, M.L., van Lenteren, J.C., and Elad, Y. (Eds.) 1999. Integrated Pest And Disease Management in Greenhouse Crops. Kluwer Academic Publishers, Dordrecht.

Aleman, J., Plana, L., Vidal, M., Llanes, G., and Delgado, M., 1998. Criterios para el control de la calidad en la cria masiva de *Lixophaga diatraeae*. *In* “Egg parasitoids” (S.A. Hassan, Ed.), pp. 97-104. Parey, Berlin.

Altieri, G. and Pinto, C., 1997. La rivoluzione della “Naturaleza” per amore e per forza Cuba a passata all’agricoltura biologica. *Mediterraneo* **1** (3), 47-56.

Altieri, M.A. and Nichols, C.I., 1999. Classical biological control in Latin America. *In* “Handbook of Biological Control” (T.S. Bellows and T.W. Fisher, Eds.) pp. 975-991. Academic Press, San Diego.

Basso, C., and Morey, C., 1990. Biological control of the sugarcane borer *Diatraea saccharalis* Fabricius (Lepidoptera: Pyralidae) with *Trichogramma* spp. (Hymenoptera: Trichogrammatidae) in Uruguay. *In* “*Trichogramma* and other Egg Parasitoids”, pp. 165-169. Les Colloques INRA 56, Paris.

Blommers, L.H.M., 1994. Integrated Pest Management in European apple orchards. Annu. Rev. Entomol. 39: 213-241.

Bolckmans, K.J.F., 1999. Commercial aspects of biological pest control. *In* “Integrated Pest and Disease Management in Greenhouse Crops” (R. Albajes, M.L. Gullino, J.C. van Lenteren and Y. Elad, Eds.), pp. 310-318. Kluwer Academic Publishers, Dordrecht.

Bueno,V.H.P., 1999. Protected cultivation and research on biological control of pests in greenhouses in Brazil**.** *Bull. IOBC/WPRS* 22 (1), 21-24.

Dominguez, E.R., 1996. Control biológico de plagas agrícolas en México. *In* “El Control Biológico en América Latina” (M.C. Zapater, Ed.), pp. 55-62. IOBC, Buenos Aires.

Federici, B.A., 1999. A perspective on pathogens as biological control agents for insect pests. *In* “Handbook of Biological Control” (T.S. Bellows and T.W. Fisher, Eds.), pp. 517-548. Academic Press, San Diego.

Ferrer, F., 1998. The use of *Telenomus remus* Nixon on commercial corn fields in Venezuela. *In* “Egg parasitoids” (S.A. Hassan, Ed.), pp. 125-130. Parey, Berlin.

Filippov, N.A., 1989. The present status and future outlook of biological control in the USSR. *Acta Entomologica Fennica* **53**, 11-18

Garcia, F., 1996. El control biológico aplicado en Colombia. *In* “El Control Biológico en América Latina” (M.C. Zapater, Ed.), pp. 31-33. IOBC, Buenos Aires.

Gelernter, W.D., and Lomer, C.J., 2000. *In “*Measures of success in biological control” (G. Gurr and S. Wratten, Eds.), pp. 297-323. Kluwer Academic Publishers, Dordrecht

Gomes, J., 1962. Histórico do combate biológico no Brasil. *Boletim do Instituto de Ecologia e Experimentação Agricolas* **21**, 89-97.

16th International Congress of Entomology, 1980. Kyoto, 3-9 August 1980. 133 pp.

Iede, E.T., and Penteado, R.C., 1998. Inimigos naturais introduzidos para o controle de *Sirex noctilio* (Hymenoptera: Siricidae) no Brasil. Resumos XVII Congresso Brasileiro de Entomologia, 9-14 Agosto 1998, Rio de Janeiro, 765.

Jackson, T.A., Alves, S.B., and R.M. Pereira, 2000. Success in biological control of soil-dwelling insects by pathogens. *In “*Measures of success in biological control” (G. Gurr and S. Wratted, Eds.), pp. 271-296. Kluwer Academic Publishers, Dordrecht

Klein Koch, C.A., 1996. Proyectos de control biológico en curso en Ecuador. *In* “El Control Biológico en América Latina” (M.C. Zapater, Ed.), pp. 41-47. IOBC, Buenos Aires.

Lenteren, J.C. van, 1993. Integrated pest management: the inescapable future. In "Modern crop protection: developments and perspectives", J.C. Zadoks ed. Wageningen Pers: 217-225.

Lenteren, J.C., van, 1997. Benefits and risks of introducing exotic macro-biological control agents into Europa. *Bull. OEPP/EPPO* 27, 15-27.

Lenteren, J.C., van, 2000. A greenhouse without pesticides: factor or fantasy? *Crop Protection* 19, 375-384.

Lenteren, J.C. van (ed.), 2003. Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. CABI Publishing, Wallingford, UK: 327 pp.

Lenteren, J.C. van, and Bueno, V.H.BP., 2003. Augmentative biological control of arthropods in Latin America. BioControl 48: 123-139.

Lenteren, J.C. van, A.K. Minks & O.M.B. de Ponti, eds., 1992. Biological Control and Integrated Crop Protection: towards environmentally safer agriculture. Pudoc, Wageningen: 239 pp.

Li, Li-Ying, 1994. Wordwide use of *Trichogramma* for biological control on different crops: a survey. *In* “Biological Control with Egg Parasitoids” (E. Wajnberg and S.A. Hassan, Eds.), pp. 37-53. CAB, Wallingford.

Macedo, N., 2000. Método de criação do parasitóide *Cotesia flavipes* (Cameron). *In* “Controle Biológico de Pragas: Produção massal e controle de qualidade” (V.H.P. Bueno, Ed.), pp. 161-174. Editora UFLA, Lavras.

Moscardi, F., 1999. Assessment of the application of baculoviruses for control of Lepidoptera. *Annu. Rev. Entomol.* **44,** 257-289.

Qin Jun-de, Meng Xiang-ling, Gong Fu-sheng, Li Shao-fu, 1992. Entomology in China. XIX International Congress of Entomology, Beijing, China : 110 pp.

Ridgway, R.L. and Vinson S.B. (Eds.) 1977. Biological Control by Augmentation of Natural Enemies: Insect and Mite Control with Parasites and Predators. Plenum, New York.

Rojas, S., 2005. Control Biológico de Plagas en Chile: Historia y avances. Libros INIA 12, Ministry of Agriculture, Instituto de Investigaciones Agropecuarias, 125 pp.

Sigsgaard, L., 2006. Biological control of arthropod pests in outdoor crops – the new challenge. Proceedings of the International Workshop "Implementation of Biocontrol in Practice in Temperate Regions – Present and Near Future". Research Centre Flakkebjerg, Denmark, November 1-3, 2005. DIAS Report No. 119 (2006), 153-167.

Smith, S.M., 1996. Biological control with Trichogramma: advances, successes and potential of their use. Annu. Rev. Entomol. 41: 375-406.

De Vis, R., Fuentes, L.E. and van Lenteren, J.C., 1999. Development of biological control of *Trialeurodes vaporariorum* with *Encarsia formosa* and *Amitus fuscipennis* on greenhouse tomato in Colombia. *Bull. IOBC/WPRS* 22 (1), 267-270.

Wang, Z, He, K, Yan S., 2005. Large-scale augmentative biological control of Asian corn borer using *Trichogramma* in China: a success story. Proc. Int. Symp. on Biological Control of Arthropods, 12-16 Sept. 2005, Davos, Switzerland. USDA Forest Service, Forest Health Technology Enterprise Team-2005-08, Vol. II: 487-494.

Zapater, M.C. (Ed.) 1996. El Control Biológico en América Latina. IOBC, Buenos Aires

6. Biological control of weeds

The section on biological control of weeds is based on and summarized from an article by R.E.C. McFadyen (2003) and was adapted by J.C. van Lenteren. All mistakes should therefore be attributed to J.C. van Lenteren.

Introduction

The economic and environmental importance of weed control is considerable, herbicides make up 47 percent of the world agricultural sales (Woodburn, 1995). In developed countries, most weed control is by application of herbicides, though mechanical weeding is increasing (Figure 1). In developing countries, weeding, usually by hand, accounts for up to 60 percent of the total preharvest labour input. Hand weeding is also applied in organic farming in developed countries (Figure 2). If uncontrolled, weeds can cause complete yield loss, and next to native weeds, invasive weeds cause enormous environmental damage. Biological control of weeds has a very successful history. Unlike the biological control of insect pests, where conservation and augmentative biological control play an important role, classical biological control is the mainstay of weed biological control. Conservation biological control is hardly used, augmentation is occasionally used with mycoherbicides and insects (see below), and in the deliberate use of grazing animals for weed control (Popay & Field, 1996).

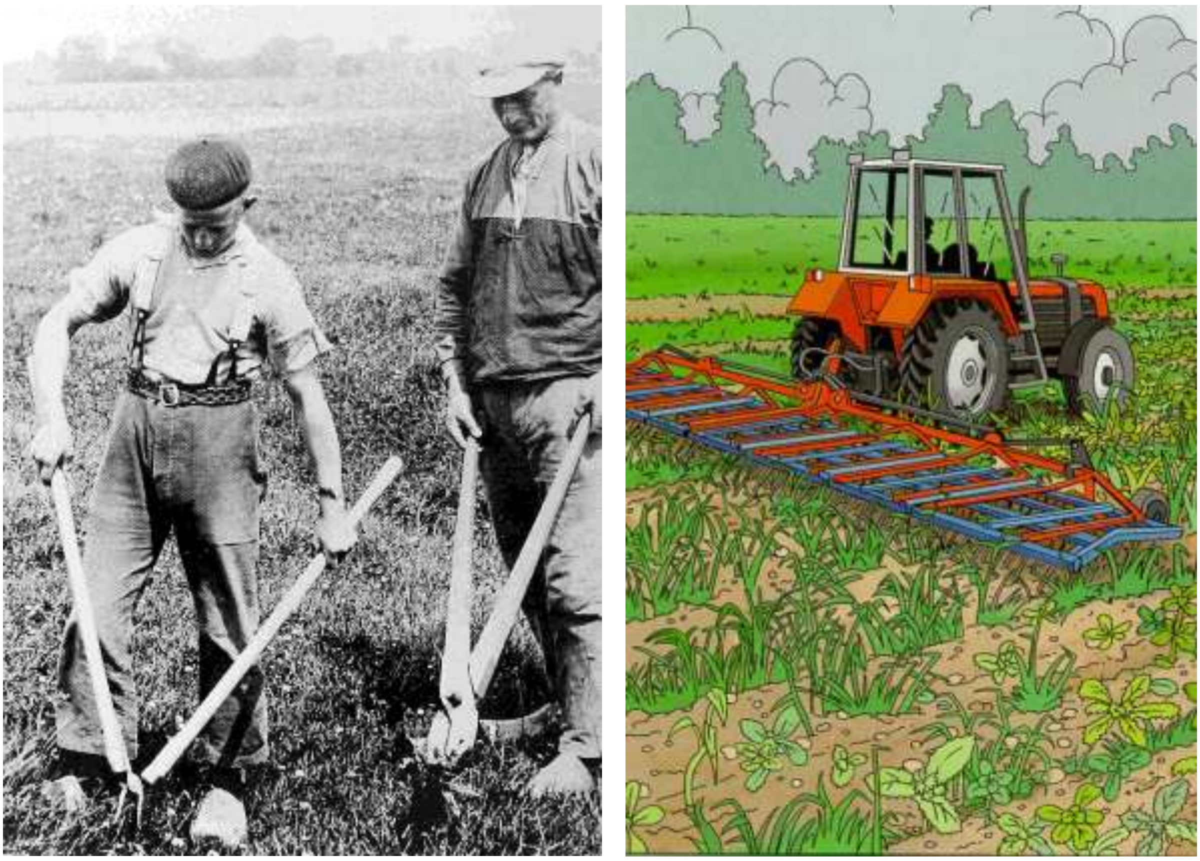


Figure 1. Left, mechanical weeding of thistles in 1930; right, mechanical weeding in 2000

Figure 2.
Hand weeding on an ecological farm in The Netherlands, 2000.

Augmentation and conservation biological control of weeds

The use of fungi to control weeds is an example of augmentation biological control. Much has been published about the use of fungi, but until now there has been little actual use in the field, though recently some successes have been obtained. One example is the use of Chondrilla Rust Fungus, *Puccinia chondrillae* for control of Skeleton Weed in Australia (Parsons & Cuthbertson, 2000). Another example is the biological control of American Bird Cherry, *Prunus serotina*, by the fungus *Chondrostereum purpureum* in Europe (De Jong et al., 1990) (Figure 3).

Native insects are sometimes used for weed control in a combination of augmentation and conservation biological control, but also here practical application is very limited (examples in Mc Fadyen, 2003).

Augmentation of exotic, introduced biological control agents is more widely used, particularly in cases where the dispersal capacity of the biocontrol agent is poor and the weed occurs in discrete scattered areas. Examples are the control of cacti in Australia and South Africa through the regular redistribution of mealybugs (Hosking et al., 1988; Moran and Zimmermann, 1991), and control of the floating fern salvinia (*Salvinia molesta*) in isolated water bodies by the salvinia weevil (*Cyrtophagous salviniae*) (McFadyen, 2003).

Classical biological control

Classical biological control of weeds has a history going back to the early 1900 (programs against lantana) and the 1920s (programs against prickly pear cactus)(Julien & Griffiths, 1998). Initially, weed biological control has tended to be concentrated on rangeland, so to countries with large areas of rangeland and in order of importance biological weed control: the USA, Australia, South Africa, Canada and New Zealand. With biological control of rangeland weeds success rates have been high. For example, Hawaii has a success rate of close to 50 percent, with 7 out of 21 weed species under complete control and significant partial control of three more (Mc Fadyen, 2003). There is an increased emphasis now on using biological control for weeds in natural ecosystems ("environmental weeds"; Figure 6). For references of weed biological programs see table 1. Europe has very few weed biological control programs (Reznik, 1996), though there are recent initiatives towards biocontrol of five major crop weeds (Scheepens et al., 2001) and proposals for biocontrol of other introduced weeds such as *Solidago altissima* (Jobin et al., 1996) and the introduced shrub *Prunus serotina* (de Jong, 2000).

Figure 3. Silver leaf symptoms on an American bird cherry, *Prunus serotina*, inoculated with the fungus *Condrostereum purpureum* (upper left), the fungus on a stem of sweet cherry, *Prunus avium* (upper right), American bird cherry stumps two years after treatment (bottom), and containers with a watery suspension of mycelium of the fungus, sold during several years as BioChon in The Netherlands (bottom right). All pictures courtesy of M. de Jong, Wageningen University.

Classical biological control of weeds depends on the introduction of natural enemies and as such are subject to legislative control. In countries with a long history of biocontrol, the legislation system is well developed and generally understood and accepted by scientists, government, and the public (see e.g. Paton, 1995). Legislative systems still need to be developed for many countries with a young weed biocontrol history, but today, the Guidelines for the export, shipment, import and release of biological control agents and other beneficial organisms (ISPM 3, IPPC 2005) can be used as a general legislative tool.

Table 1. Recent reviews of weed biological control programs

Continent / Country / State	Reference
Africa south of the Sahara	Julien et al., 1996
Asia	Ooi, 1992
Australia	Julien & Griffiths, 1998; Briese, 2000
Canada	Harris, 1993
Eastern Europe	Reznik, 1996
Hawaii	Gardner et al., 1995
New Zealand	Julien & Griffiths, 1998
South Africa	Hoffmann, 1995
United States of America, continent	Goeden, 1993

Procedures in classical biological control of weeds

The selection of weed targets for biological control is based on the benefits to be achieved plus the estimates of the probability of success. The more widespread and damaging the weed, the greater the potential benefits. Costs and benefits are easier to estimate for rangeland weeds than for environmental weeds. Serious conflict of interest may arise when a plant is a weed in one situation and a valuable plant in another. Once the decision has been made that a classical biological program for a weed will be executed, a stepwise approach is followed involving foreign exploration, selection and testing of agents, rearing and release, and post release evaluation (Wapshere et al., 1989).

Agent selection

During foreign exploration, correct identification of the weed in its country of origin is required, which is nowadays based on classic taxonomy combined with modern molecular biological methods. These methods also facilitate the collection of biocontrol agents from the correct strain and locality. Agent selection is the critical step and the choice of the best agent is the “holy grail” of weed biocontrol as well as in biological control of other organisms. In 1991, each agent tested and introduced cost US$ 400 000 or three scientist years (Harris, 1991), which with technical support and facilities, would be about US$ 500 000 in 2001 (McFadyen, 2003). Over the years there have been many theories or protocols on how to choose the best agent (Harris, 1991; Goeden, 1993). Protocols for agent selection, although useful discussion points, have proved of little or no predictive value, with the exception of host specificity studies (Blossey, 1995, Gassmann & Schroeder, 1995). The major problem with prediction is that success does not depend on features of the insect as much as upon environmental factors such as climate and the presence of parasitoids or predators of the biocontrol agent. For a further discussion of the value of predictive studies, the reader is referred to McFadyen (2003) and references in that book chapter.

Host specificity testing

The necessity for detailed host specificity testing before introducing a new weed biocontrol agent is an accepted principle in weed biocontrol. In arthropod biocontrol this principle seems to have become accepted only recently (Kuhlmann et al, 2006, van Lenteren et al., 2006). Due to this host specificity testing in weed biological control, "disasters" in the history of weed biocontrol are hardly known (McFadyen, 2003). Over the years, host specificity testing has developed from the testing of long lists of plants unrelated to the host weed, to use of targeted lists of plants closely related to the weed and including native plants (Wapshere, 1989; Blossey, 1995). Tests for immature and mature herbivores have been developed and test results are published in entomological and biocontrol journals, and in the proceedings of the International Symposia on Biological Control of Weeds.

The major problem for any biocontrol researcher, so also in weed biocontrol, is the interpretation of results where feeding occurs in the laboratory or greenhouse tests but not in the field. This problem of finding false positives can sometimes be solved by additional testing. Testing must take into account the possibility that very high populations developing on the host weed may result in starving insects dispersing onto adjacent plants, where transient, but significant damage may occur even if development or long-term survival is not possible. For this reason, some kind of non-choice test on closely related plants "at risk" must be part of the testing (Wapshere, 1989). Host specificity testing can never give absolute answers and guarantee that the agent will never attack other plants, but provides the basis for a risk assessment. The decision whether or not to release an agent is ultimately political, where the risks of release are weighed against the consequences of alternative control methods. In the past, agents have been released in the knowledge that they would attack nontarget plants, where the relative value of the nontarget plant was significantly lower than the damage (economic or environmental) being caused by the weed (McFadyen & Marohasy, 1990; Olckers et al., 1995).

Post release evaluation

In the past, little follow-up evaluation has been done, chiefly because financial sponsors took the view that it would be obvious whether or not the weed was successfully controlled (Blossey, 1995). For a proper post release study, one needs a pre-release evaluation of the distribution and density of the weed, but also these are often not done. However, recently, several pre-release studies have been performed; see examples in McFadyen (2003). A proper post release study involves a study of the distribution and density of the released agent(s) and its impact on the weed population over time.

Post release evaluation also includes studies on damage to nontarget plants. There are very few documented cases of damage to nontarget plants resulting from the introduction of insects for the biocontrol of weeds (McFadyen, 2003). In the early years of weed biocontrol, attack of native plants of no economic value was not seen as a problem. An example is the attack of native *Senecio* species by the cinnabar moth *Tyria jacobaeae* in Canada and the USA (Diehl & McEvoy, 1990) (Figure 6). Nowadays, such cases of nontarget attack are evaluated carefully. An example is the concern that *Cactoblastis cactorum*, successfully released to control *Opuntia* cacti without nontarget effects in Australia, will create problems by not only eating damaging native cacti in the Caribbean such as *Opuntia triacantha*, but also rare species of cacti (Simberloff & Stiling, 1996; Zimmerman et al., 2004) (Figure 4). Therefore, despite the long history of successful and safe biocontrol of weeds, practitioners do recognize the risk involved and apply increasingly advanced environmental risk assessment methods.

Figure 4. Adult (upper left) and caterpillars (upper right) of *Cactoblastis cactorum*, natural enemy of Prickly Pear (*Opuntia* sp.). Prickly Pear flower and fruit (middle left and centre). Prickly pear before (middle right and lower left) and after release (lower right and lower middle) of *Cactoblastis cactorum* in Australia.

Results achieved

For the classification of success, weed biocontrol researchers are using a terminology that slightly differs from that used in arthropod biocontrol. Hoffmann (1995) proposed the following definitions:

- Complete: when no other control method is required or used, at least in areas where the agent(s) are established (complete control does not mean that the weed is eradicated);
- Substantial: where other methods are needed but less effort is required (e.g., less herbicide or less frequent application);
- Negligible: where despite damage inflicted by agents, control of the weed is still dependent on other control measures.

Success rates are generally quoted as 60% percent of agents introduced resulting in successful establishment, and 33 percent of these resulting in control (Crawley, 1990), but of greater importance is the proportion of programs that achieve successful control. Data provided in McFadyen (2003) show that the overall success rate of weed biological control programs in South Africa, Hawaii, and Australia is 50-80 percent. In early programs, very small releases of biocontrol agents were usually made and establishment rates were consequently poor. Nowadays, large numbers are released and establishment rates are now approaching 100 percent (Blossey et al., 1996). The track-record of weed biological control shows that as per the year 2000, 41 weed species have been successfully controlled somewhere in the world using introduced insects and pathogens (McFadyen, 2000). With many of these weeds, the successful control has been repeated in several countries and regions of the world and the savings to agriculture and the environment are enormous. Benefit cost ratios are in the order of 2.3 to 110:1; and these ratios increasing each year as chemical control is no longer needed. Benefits and costs are hard to determine for environmental weeds. An overview of benefits and costs, as well as an overview of recent successes is provided by McFadyen (2003) and some are listed in table 2. Weed species brought under complete control are from very different groups and represent annual agricultural and environmental weeds, water weeds, perennial shrubs and trees. Financial and social benefits from control of water hyacinth (Figure 5) and salvinia in particular have been enormous. Because waterways are used for transport and fisheries, irrigation and water supply, an entire society can be disrupted or even destroyed if dense mats of floating water weeds prevent movement between settlements. When salvinia was brought under biological control in Sri Lanka, the benefit cost ratio was calculated to be 1675:1; costs were so low because the natural enemy had already been tested and used elsewhere.

Table 2. Major recent successes in weed biological control

Weed species brought under biological control	Continent/Country/ State	Reference
Acacia saligna, golden wreath wattle	South Africa	Morris, 1997, Hoffmann & Moran, 1998
Ageratina riparia, hamakua pamakani	Hawaii	Gardner et al., 1995
Alternanthera phileroxoides, alligator weed	Subtropics	Julien & Chan, 1992
Carduus nutans, nodding thistle	Canada	McFadyen, 2003
Chromolaena odorata, jack in the bush	Africa, Asia	McFadyen, 2003
Cordia curassavica, black sage	Malaysia	Ooi, 1992
Eichhornia crassipes, water hyacinth	Tropics, subtropics	Julien et al., 1996
Harrisia martinii, harrisia cactus	Australia	McFadyen, 1986
Hypericum perforatum, klamath weed	Hawaii, continental USA	Gardner et al., 1995
Mimosa invisa, sensitive plant	Australia, New Guinea	Ablin 1995
Pistia stratiotes, water lettuce	Tropics, subtropics	Julien et al., 1996
Salvinia molesta, salvina	Tropics, subtropics	Julien & Griffiths, 1998
Senecio jacobaea, tansy ragwort	Australia, USA	Coombs et al., 1995; McEvoy et al., 1991
Sesbania punicea, rattle box	South Africa	Morris, 1997, Hoffmann & Moran, 1998
Xanthium occidentale, noogoora burr	Australia	Chippendale, 1995
Chondrilla juncea, skeleton weed	Australia	Marsden et al., 1980

Figure 5. Dense mats of Water Hyacinth, *Eichhornia crassipes*, (upper left), its flowers (middle), and the beetle *Neochetina eichhorniae* used for control (right).

Figure 6. Field with the weed Tamsy Ragwort, *Senecio jacobaea*, (upper left), adult (lower left) and caterpillar (lower right) of *Tyria jacobaea*e, a natural enemy of Ragwort, and Ragsort stems with caterpillars of Tyria (upper right)

Future of weed biological control

Plant introductions for forestry, pasture and ornamentals have increased greatly recently, which are expected to lead to increased weed problems after a lag-time of some 50 years (Hughes, 1995). It seems bizarre that, unlike weed biocontrol agents, plant introductions are not subject to controls in many countries while they have resulted in many very serious problems. Alien plant invasions now affect conservation areas on every continent except Antarctica. As a result, conservation scientists and managers are increasingly accepting that "biocontrol is the only resort when the invasion is 'out of control' " (Cronk & Fuller, 1995), but this understanding has not reached the general conservation community, let alone the public as a whole. Still, for many weed problems, and particularly for the ones in natural areas, biological control will be the only feasible solution, as extensive use of herbicides or mechanical control methods in conservation areas would be vary damaging as well as prohibitively expensive. The FAO now regards biocontrol of weeds as the major option to be promoted and currently supports large programs in Latin America and Africa.

References:

Ablin, M.P., 1995. *Heterospylla* sp. (Psyllidae) successfully controls pasture infestations of *Mimosa invisa* within three years of release in Australia. In Proc 8th Symposium on Biological Control of Weeds, E.S. Delfosse and R.R. Schott (eds.). CSIRO, Melbourne, pp. 435-436.

Blossey, B., 1995. A comparison of various approaches for evaluating potential biological control agents using insects on *Lythrum salicaria*. Biological Control 5: 113-122.

Blossey, B., Malecki, R.A., Schroeder, D. and Skinner, L. 1996. A biological control program using insects against purple loosestrife, *Lythrum salicaria*, in North America. In Proc. 9th Int. Symp. Biol. Control of Weeds, V.C. Moran and J.F. Hoffmann (eds.), University of Capetown, Stellenbosch, pp. 351-355.

Briese, D.T., 2000. Classical biological control. In Australian Weed Management Systems, B. Sindel (ed.). R.G. and F.J. Richardson Publications, Melbourne, Australia, pp. 161-192.

Chippendale, J.F., 1995. The biological control of Noogoora burr (*Xanthium occidentale*) in Queensland: an economic perspective. In Proc 8th Symposium on Biological Control of Weeds, E.S. Delfosse and R.R. Schott (eds.). CSIRO, Melbourne, pp. 185-192.

Coombs, E.M., Isaacson, D.L. and Hawkes, R.B., 1995. The status of biological control of weeds in Oregon. In Proc 8th Symposium on Biological Control of Weeds, E.S. Delfosse and R.R. Schott (eds.). CSIRO, Melbourne, pp. 463-471.

Crawley, M.J., 1990. Plant life-history and the success of weed biological control projects. In Proc. 7th Int. Symp. Biol. Control Weeds, E.S. Delfosse (ed.). Min. Agric. Forest. Rome, pp. 17-26.

Cronk, Q.C.B. and Fuller, J.L., 1995. Plant Invaders: The Threat to Natural Ecosystems. People and Plants Conservation Manuals, WWF International, Chapman and Hall, London, 241 pp.

de Jong, M., 2000. The BioChon story: deployment of Condrostereum purpureum to suppress stump sprouting in hardwoods. Mycologist, 14(2): 58-62.

de Jong, M., Scheepens, P.C., and Zadoks, J.C., 1990. Risk analysis for biological control: a Dutch case study in biocontrol of Prunus serotina by the fungus Chondrostereum purpureum. Plant Disease 74(3): 189-194.

Gardner, D.E., Smith, C.W. and Markin, G.P., 1995. Biological control of alien plants in natural areas of Hawaii. In Proc 8th Symposium on Biological Control of Weeds, E.S. Delfosse and R.R. Schott (eds.). CSIRO, Melbourne, pp. 35-40.

Gassmann, A. and Schroeder, D., 1995. The search for effective biological control agents in Europe: history and lessons from leafy spurge (*Euphorbia esula* L.) and cypress spurge (*Euphorbia cyparissias* L.). Biological Control 5, 466-477.

Goeden, R.D., 1993. Arthropods for the suppression of terrestrial weeds. Proc. Beltsville Symp. 18, Pest Management: Biologically Based Technologies. ARS, USDA, American Chemical Society, Washington DC, pp. 231-237.

Harris, P., 1991. Classical biological control of weeds: its definition, selection of effective agents, and administrative-political problems. Canadian Entomologist 123, 827-849.

Harris, P., 1993. Effects, constraints and the future of weed biological control. Agric. Ecosyst. Environ. 46: 289-303.

Hoffmann, J.H., 1995. Biological control of weeds: the way forward, a South African perspective. Proc. BCPC Symp. Weeds in a Changing World 64: 77-89.

Hoffmann, J.H. and Moran, V.C., 1998. The population dynamics of an introduced tree, *Sesbania punica*, in South Africa, in response to long-term damage caused by different combinations of three species of biological control agents. Oecologia 114: 343-348.

Hosking, J.R., McFadyen, R.E.C. and Murray, N.D., 1988. Distribution and biological control of cactus species in eastern Australia. Plant Prot. Quart. 3: 115-123.

Hughes, C.E., 1995. Protocols for plant introductions wih particular reference to forestry: changing perspectives on risks to biodiversity and economic development. Proc. BCPC Symp. Weeds in a Changing World 64, 15-32.

IPPC (International Plant Protection Convention), 2005. Guidelines for the export, shipment, import and releasse of biological control agents and other beneficial organisms (ISPM (International Standard for Phytosanitary Measures, No. 3). Also available on internet via www.FAO.org or www.IPPC.org

Jobin, A., Schaffner, U. and Nentwig, W., 1996. The structure of the phytophagous insect fauna on the introduced weed *Solidago altissima* in Switzerland. Entomol. Exp. Appl. 79: 33-42.

Julien, M.H. and Chan, R.R., 1992. Biological control of alligator weed: unsuccessful attempts to control terristrial growth using the flea beetle *Disonycha argentinensis* (Coleoptera: Chrysomelidae). Entomophaga 37, 215-221.

Julien, M.H., Harley, K.L.S., Wright, A.D., Cilliers, C.J., Hill, M.P. et al., 1996. International cooperation and linkages in the management of water hyacinth with emphasis on biological control. In Proc. 9th Int. Symp. Biol. Control of Weeds, V.C. Moran and J.F. Hoffmann (eds.), University of Capetown, Stellenbosch, pp. 273-282.

Julien, M.H. and Griffiths, M., 1998. Biological Control of Weeds: a World Catalogue of Agents and their Target Weeds. CAB International, Wallginford, Oxon.

Kuhlmann, U., Schaffner, U. and Mason, P.G., 2006. Selection of non-target species for host specificity testing. In: Bigler F., Babendreier D., Kuhlmann U., eds. *Environmental Impact of Invertebrates for Biological Control of Arthropods: Methods and Risk Assessment*. Wallingford, UK: CAB Int.: 15-37.

Marsden, J.S., Martin, G.E., Parham, D.J., Risdill-Smith, T.J. and Johnston, B.G., 1980. Skeleton weed control. In Returns on Australian Agricultural Research, CSIRO Division of Entomology, Canberra, pp 84-93.

McEvoy, P.B., Cox, C.S. and Coombs, E.M., 1991. Succesful biological control of ragwort. Ecol. Applic. 1, 430-432.

McFadyen, R.E.C., 1986. Harrisia cactus in Queensland. In R. Kitching (ed.) The Ecology of Exotic Animals and Plants in Australia. Jacaranda-Wiley, Brisbane, pp. 240-261.

McFadyen, R.E.C. and Marohasy, J.J., 1990. A leaf-feeding moth, Euclasta whalleyi (Lepidoptera: Pyralidae), for the biological control of *Cryptostegia grandiflora* (Asclepiadaceae) in Queensland, Australia. Entomophaga 35, 431-435.

McFadyen, R.E.C., 2000. Sucesses in biological control. In N.R. Spencer (ed.), Proc. Xth Int. Symp. Biol. Control Weeds, Montana State University, Bozeman, MT, pp. 3-14.

McFadyen, R.E.C., 2003. Biological control of weeds using exotic insects. In: Predators and Parasitoids (O. Koul & G.S. Dhaliwal, eds.). Taylor & Francis, London, pp. 163-183.

Moran, V.C. and Zimmermann, H.G., 1991. Biological control of jounted cactus, *Opuntia aurantiaca* (Cactaceae) in South Africa. Agric. Ecosyst. Environ., 27: 5-27.

Morris, M.J., 1997. Impact of the gall-forming rust fungus *Uromycladium tepperianum* on the invasive tree Acacia saligna in South Africa. Biol. Contr. 10, 75-82.

Olckers, T., Zimmermann, H.G. and Hoffmann, J.H., 1995. Interpreting ambiguous results of host-specificity tests in biological control of weeds: assessment of two *Leptinotarsa* species (Chrysomelidae) for the control of Solanum elaeagnifolium (Solanaceae) in South Africa. Biol. Contr. 5, 336-344.

Ooi, P.A.C., 1992. Biological control of weeds in Malaysian plantations. Proc. Int. Weed Cont. Congr., Weed Science Society Victoria, Melbourne, pp. 248-255.

Parsons, W.T. & Cuthbertson, E.G. (2000). Noxious Weeds of Australia. 2nd edn. Inkata Press. See also http://www.weeds.org.au/

Paton, R., 1995. Legislation and its administration in the approval of agents for biological control in Australia. In Proc 8th Symposium on Biological Control of Weeds, E.S. Delfosse and R.R. Schott (eds.). CSIRO, Melbourne, pp. 653-658.

Popay, K. and Field, R., 1996. Grazing animals as weed control agents. Weed Technology, 10: 217-231.

Reznik, S.Y., 1996. Classical biological control of weeds in crop rotation: a story of a failure and prospects for success. In Proc. 9th Int. Symp. Biol. Control of Weeds, V.C. Moran and J.F. Hoffmann (eds.), University of Capetown, Stellenbosch, pp. 503-506.

Scheepens, P.C., Muller-Scharer, H. and Kempenaar, C., 2001. Opportunities for biological weed control in Europe. BioControl 46: 127-138.

van Lenteren, J.C., Cock, M.J.W, Hoffmeister, T.S., Sands, D.P.A., 2006. Host specificity in arthropod biological control, methods for testing and interpretation of the data. In: Bigler F., Babendreier D., Kuhlmann U., eds. *Environmental Impact of Invertebrates for Biological Control of Arthropods: Methods and Risk Assessment*. Wallingford, UK: CAB Int.: 38-63.

Woodburn, A.T., 1995. The market for agrochemicals: present and future. Proc. Brighton Crop Prot. Conf. – Weeds. 1. 121-128.

Zimmermann, H., Bloem, S. and Klein, H., 2004. Biology, history, threat, surveillance and control of the Cactus Moth, *Cactoblastis cactorum*. IAEA, Vienna, June 2004, 40 pp.

7. Future of biological control: to be written

Table 1. Present and estimated future use of biological control and biologicallly based pest control technologies (source, van Lenteren unpublished)

Technology	importance	
	present	future
natural biological control (NBC)	+++	+++
inoculative, classical biological control (CBC)	+++	+++
augmentative (inundative/seasonal inoculative) biocontrol (ABC)	+	++
viruses	+	++
bacteria	+	++
fungi	+	++
nematodes	+	+
mass-reared arthropods	+	++
microbially produced toxins	++	+++
natural compounds / botanicals	++	++
genetically manipulated plants against pests	++	+++
genetically manipulated biocontrol agents	-	?
host-plant resistance	+++	+++
behaviour modifying chemicals	+	++

Rice in Indonesia: from regular pesticide applications to conservation biological control

8. Evaluation and ranking of natural enemies: from art to science

The material used for this chapter originates from van Lenteren (1980, 1986a, b) and van Lenteren & Manzaroli (1999)

1. Introduction

Natural enemies can be used in the following release strategies (Fig. 1):

(i) The *inoculative release* method is also known as “classical” biological control and is synonymous with importation. The beneficial organisms are collected from one part of the world and introduced into the area where the pest occurs (Fig. 1 top). Only a relatively small number of beneficial organisms is released; the aim is long-term control. The method is usually applied in forest and orchard ecosystems where continuous existence of natural enemies can be guaranteed. An example of a successful European programme is the introduction of the parasitoid *Aphelinus mali* (Haldeman), against the apple woolly aphis, *Eriosoma lanigerum* (Hausmann) into France in 1920, and later into other European countries.

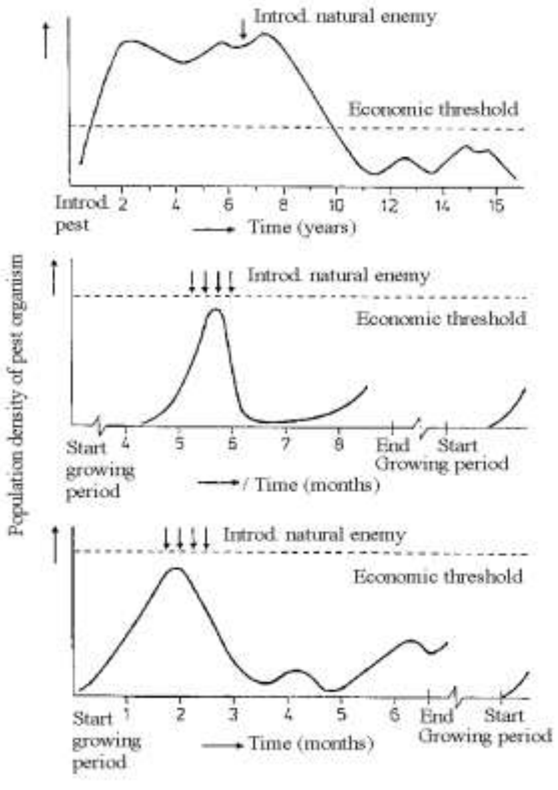


Figure 1. Different biological control strategies: inoculative releases (top), inundative releases (middle) and seasonal inoculative releases (bottom).

(ii) The *inundative release* method is where beneficial organisms are collected, mass reared and periodically released in large numbers to obtain immediate control of a pest (i.e. use as a biotic insecticide; Fig. 1 middle). Pest control is mainly obtained from the released natural enemies and not from their offspring. Inundative releases are applied to crops where viable breeding populations of the natural enemy are not possible or in crops where the damage threshold is very low and rapid control is required at very early stages of infestation. Examples are the use of *Diglyphus begini* (Ashmead) to control *Liriomyza trifolii* (Burgess) on marigolds and *Encarsia formosa* Gahan to control *Bemisia tabaci* (Gennadius) on Poinsettia (Parrella, 1990). Inundative releases of *Chrysoperla carnea* (Stephens) larvae are applied against aphids on strawberry in northern Italy (Celli *et al.*, 1991) to obtain good control within a few days. This is achieved by releasing *Chrysoperla* at the 3rd larval stage which has the greatest predation capacity. Predation stops completely when the 3rd stage *Chrysoperla* larvae are close to pupation. The application of the entomopathogenic fungus *Verticillium lecanii* (A. Zimmerm.) Viégas for the control of whitefly and sprays with the *Spodoptera* NPV virus can also be considered inundative releases.

(iii) The *seasonal inoculative release* method is where natural enemies are collected, mass reared and periodically released into short-term crops (6–12 months) and where many pest

Successful natural enemies in inoculative releaeses (*Aphelinus mali*, left), in inundative releases (*Spodoptera* NPV virus, middle), and in seasonal inoculative releases (Diglyphus isaea,right)

generations occur (Fig. 1 bottom). A relatively large number of natural enemies is released to obtain both immediate control and a build-up of the natural enemy population for control throughout the same growing season. This method can be applied when the growing method of a crop prevents control extending over many years, for example in greenhouses where the crop together with the pests and natural enemies are removed at the end of the growing season. The method is distinctly different from the inundative method, and more closely resembles the inoculative method because control is obtained for a number of generations of the pest and control would be permanent if the crop were grown for a much longer period. The seasonal inoculative release method has been developed in Europe during the last two decades and is applied with commercial success in greenhouses. Two well-known natural enemies used for this approach are the spider mite predator *Phytoseiulus persimilis* Athias-Henriot and the whitefly parasitoid *E. formosa*.

Another important aspect of biological control can be *conservation of natural enemies* whereby the environment is manipulated or modified to improve the effectiveness of already established natural enemies through: (i) provision of missing or inadequate requisites such as alternative hosts, supplementary food or shelter; and (ii) by elimination or mitigation of hazards or adverse environmental factors such as poor cultural practices, indiscriminate use of insecticides and other adverse physical or biotic factors. An example of (i) is the placement of alternative food (eggs of *Ephestia kuehniella* Zeller) for the nymphs and adults of the predatory bug *Macrolophus caliginosus* Wagner at times when its preferred whitefly prey is absent. The current very careful use of (selective) pesticides in greenhouses to prevent mortality of natural enemies illustrates tactic (ii).

An often neglected aspect of biological control is the phenomenon of *natural control*: many potential pest organisms are kept at densities well below the damage threshold by natural enemies that occur in the field. In natural ecosystems, a myriad of natural enemy species maintain plant-eating insects at low population densities. Even in agro-ecosystems, many potential pests are held at non-damaging levels by natural enemies which occur naturally. DeBach and Rosen (1991) estimate that more than 90% of all agricultural pest species are under natural control. Even in greenhouses natural control can play an important role: in northern Europe, parasitoids of leafminers, and predators and parasitoids of aphids invade greenhouses in April or May and result in pest control free of charge. In Mediterranean Europe, greenhouses are more open than in northern Europe, and natural control can be very important because natural enemies can easily move into the greenhouses from the field. Overlapping plantings of the same crops and abundant wild plants on which both the pest and the natural enemies can breed, creates good conditions for natural control, very often without any special intervention. High numbers of predators and parasitoids may survive and remain active during the Mediterranean winter. For example the parasitoid *Diglyphus isaea* (Walker) can develop on several leafminer species and it often migrates into early-season, newly-transplanted crops in greenhouses, and keeps the leafminers *Liriomyza bryoniae* (Kaltenbach), *L. trifolii* and *Liriomyza huidobrensis* (Blanchard) below the damage threshold (Calabretta *et al.*, 1995). Another example of natural enemies providing natural control is the whitefly predator, *M. caliginosus*. This predator is very common throughout the Mediterranean basin and can survive on wild plant species like *Inula viscosa* (L.) Ait. (Arzone *et al.*, 1990). If it is not killed by insecticides, it can be a key factor in reducing whitefly populations (Alomar *et al.*, 1994).

2. How to Develop a Biological Control Programme?

The planning of a biological control project and a procedure to evaluate natural enemies prior to introduction will be presented in this section.

2.1. *Planning of a project*

The typical way to tackle a biological control project is as follows (Fig. 2):

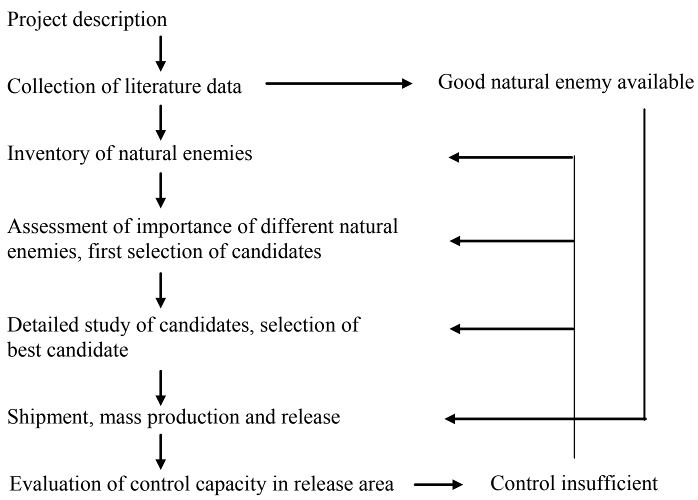


Figure 2. Phases in the development of a biological control project.

(i) A project description is prepared. This includes the taxonomic and pest status of the target organism.

(ii) Information on the biology of the pest and its natural enemies is collected through literature research and correspondence. If a good natural enemy is identified and available one may proceed to step (vi).

(iii) If an appropriate natural enemy is not available, then an area has to be selected for exploration. This is usually the area of origin of the pest organism. Inventory research can now be started. It is important to collect sufficient animals and to ensure the genetic diversity of natural enemies.

(iv) The importance of the different natural enemies in the exploration area should be estimated. The host range must be studied and negative characteristics (e.g. hyperparasitic habits) noted. These data are used to make a first selection of species for future studies. Although studies in the exploration area cannot be used to predict whether a new natural enemy species will become established or be effective in a new environment, they can show if an agent is clearly unsuitable.

(v) After the first selection a more detailed study can be made with the chosen species. Depending on the type of programme in which natural enemies will be used, a number of the characteristics mentioned in Section 2.2 may be studied.

(vi) The selected species of natural enemies are mass produced and released in the area where the pest has to be controlled.

(vii) After release and establishment of the natural enemy, determine its effectiveness (both biological and economic effectiveness) in the target area.

The most critical phases in any biological control programme are the steps where selection of natural enemies takes place [(iii), (iv) and (v)]. Many of the greenhouse pests in countries with a temperate climate have been introduced on the imported infested plant material. This is quite different from the pest situation in greenhouses in (sub)tropical (e.g. Mediterranean) countries, where pest organisms may migrate into greenhouses from surrounding fields. In northwestern Europe, 75% of the species of greenhouse pests, i.e. some 40 species, have been accidentally introduced into the region (for examples, see van Lenteren, 1997). The natural enemies used for biological control of these pests originate from a great variety of sources. Handbooks on biological control generally recommend that natural enemies be collected in the area where the pest is native (e.g. Huffaker and Messenger, 1976). In greenhouse biological control research we have found that it is worth trying introduced natural enemies against native pests, and endemic natural enemies against introduced pests; any dogmatism in selection of natural enemies seems to be counter productive. A good illustration of this is the discovery that several European parasitoids (*Opius*, *Dacnusa* and *Diglyphus* species) can give good control of exotic leafminer (*Liriomyza*) species which were accidentally imported. So we learned that all kinds of combinations of exotic/endemic pests and exotic/endemic natural enemies may result in good biological control.

Phytoseiulus attacking *Tetranychus*

An important consideration when selecting natural enemies and setting up mass production, is the quality of the starting population of the natural enemy. The initial stock for a laboratory colony should preferably be large and should contain genetically diverse material (e.g. Huffaker and Messenger, 1976). Such statements are easily formulated, but often not easy to achieve. Many of the colonies of natural enemies used for biological control were started from very small populations (for examples, see e.g. van Lenteren and Woets, 1988). An interesting example is the history of *P. persimilis*. This predatory mite accidentally reached Germany in 1959 on plant material imported from Chile. Less than 10 individuals reached The Netherlands in that same year, and these were the basis of research that was started to find out if the predator could be used for control of pest mites. Many commercial colonies of *P. persimilis* in the 70s and 80s originated from this very small population, and pest control with this predator was generally very good. We do not give this example to suggest that there is no need to collect large founder populations, but rather to show that if it is difficult to obtain large numbers it might still be useful to do experiments with a new natural enemy. On the other hand, if control results are poor with a natural enemy species that was started from a very small colony, it might be worth trying it again after collecting a larger number of individuals. There are important examples in the literature showing the existence of large differences between populations of the same natural enemy species, which can result in either failure or success of biocontrol (e.g. Huffaker and Messenger, 1976).

The above outline for planning of a project needs to be adapted for each specific case of biological control and often ad hoc problems make it necessary to deviate from the general procedure.

2.2. *Pre-introductory evaluation of natural enemies*

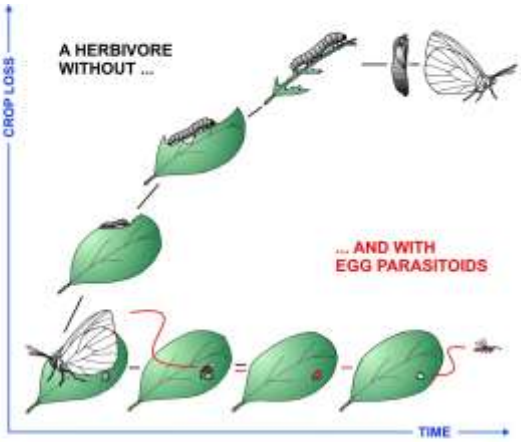
How it Was

Until now the selection of natural enemies for biological control programmes has been an empirical procedure, like the selection of the majority of the chemical pesticides. Most natural enemies have been found through trial-and-error. During the 100 or more years in which biological control has been practised, some 5500 introductions of natural enemies into new areas (168 countries) were made, and about 1500 of these introductions resulted in establishment of the species. Long lasting control was obtained in 420 cases resulting in a considerable reduction of pest problems. The success ratio of 1 out 20 in biological control is good when compared with chemical control, where it is 1 out of 20,000. Still, some biological control workers are of the opinion that the selection process should be much improved for two main reasons: first to prevent a lot of time being spent on ineffective natural enemies, and secondly, to be able to work fast and reliably during the coming decades when many new natural enemies need to be identified for use in biological control.

Finding the right natural enemy

Many researchers have thought about ways of optimizing the pre-introductory selection from the large array of natural enemies, so as to increase the predictability of success before introductions are made (for a more detailed discussion, see van Lenteren, 1993). A biological control project can be characterized as a process whereby a diverse natural enemy complex is reduced to a few candidates for introduction. The selection process is still often highly arbitrary and not related to any aspect of an agent which might indicate its potential value. However, it is a fact that programmes usually end before all promising agents have been introduced. Hence prioritizing agents on the basis of their likely efficiency would ensure that the best species are released. It would be much better for our profession if deliberate choices between possible candidates are made, particularly if this leads to a halt in importation of useless candidates. Further, if we intend to change biological control from an art into science, we should develop a basic understanding of how biological control works and be able to make predictions about the outcome of introduction programmes.

Three approaches for the pre-release selection of natural enemies emerge from the literature: (i) evaluation based on individual attributes of natural enemies; (ii) evaluation based on integration of individual attributes; and (iii) evaluation based on ecosystem studies (Mackauer *et al.*, 1990). In the evaluation based on individual attributes of natural enemies, agents are selected on the basis of particular biological attributes or life-history characteristics (e.g. duration of development, fecundity, searching efficiency). Theory dissects natural enemies into simple sets of characters, which can be viewed and compared independently. This approach is no longer popular, although it is still used. In the evaluation based on integration of individual attributes, a composite picture is developed of the pest reduction potential of the natural enemy. When carefully applied, this method has proved to be valuable. The evaluation based on ecosystem studies proceeds from the theoretical notion of how natural enemies fit into the broad ecology of the pest and its other mortality factors. Here, community concepts predominate, expressed in arguments for density-specific agent complexes, multiple introductions and filling "empty" natural enemy niches. This approach is not often applied, but strongly supported by some biocontrol workers. Although it is scientifically attractive, it is not usable yet and it will take many more years before it is workable.



Courtesy Prof. F. Bin

Currently, there are good evaluation criteria available to allow for a choice between useless and potentially promising natural enemies (see below). Such a choice prevents useless research on and introduction of inefficient natural enemies. With a gradual improvement of evaluation criteria and a further integration of criteria, ranking among the promising natural enemies will be possible. A pre-introductory evaluation procedure takes some 18 months per natural enemy or considerably shorter when the natural enemy shows very obvious inherent weaknesses. In that case no further money is spent on rearing, release and follow up studies of unsuitable natural enemies. The data from this research are not only useful for selection, but also provide essential information for designing a mass production method, the type of releases (inundative, seasonal inoculative), the release programme (timing, spacing and numbers to be released) and an extension programme.

Criteria for Evaluation of Natural Enemies

A compilation of the criteria which are mentioned in the biological control literature leads to the following list (Table 2; van Lenteren, 1986a):

(i) Seasonal synchronization of the natural enemy with its host/prey is important in inoculative releases ("the natural enemy has to be around when the pest occurs"). When using seasonal inoculative and inundative releases, as in greenhouses, this synchronization can be obtained by the grower through releasing natural enemies when most pest insects are in the developmental stage for optimal attack. Adjustments can be made throughout the growing season.

(ii) The natural enemy must develop to the adult stage on the pest insect in order to obtain ongoing control. If the natural enemy kills the host but cannot develop on it, the natural enemy will have to be re-introduced in each subsequent pest generation. This requires an inundative programme which is more expensive. Further, natural enemy development should be synchronous with that of the pest species so that, for example, adult parasitoids are available when suitable pest stages are present for parasitization (internal synchronization). This is especially important at the start of the growing season in greenhouses when pest generations are often still discrete. Poor synchronization can be corrected in part through repeated introductions. Later in the growing season, when generations of the pest organism overlap, this problem ceases to be important.

(iii) At an early stage of pre-introductory research, tests should be performed to determine whether the natural enemies are able to develop, reproduce and disperse in the climate conditions under which they will be used in the greenhouse.

(iv) Also at an early stage of the evaluation process, potential negative effects should be considered. The natural enemies should not attack other beneficial organisms in the same environment or non-target species in the area where they are to be introduced.

(v) Mass production of natural enemies is usually unnecessary for inoculative release programmes, but good culture methods are the basis for the successful inundative and seasonal inoculative biological control programmes used in greenhouses. Culture methods largely determine the eventual cost of the natural enemy and the probability of its commercial application.

(vi) In crops where different insect species (both non-pest and pest species) may occur it is important to introduce natural enemies that preferentially attack pest species in order to obtain adequate pest reduction. A narrow host/prey range is desirable. In greenhouses with relatively few phytophagous species this is less important than in outdoor fields.

(vii) Several biocontrol workers have stated that an efficient parasitoid should have a potential maximum rate of population increase (r_m) equal to or larger than that of its host. If the parasitoid oviposits in the host and also causes additional substantial mortality (e.g. through host feeding or host mutilation), we should reformulate the previous sentence to: "an efficient parasitoid should cause an overall host kill rate larger than the rate of population increase of the host in the absence of the natural enemy". For efficient predators this would mean that they should have a prey kill rate which is larger than the r_m of the prey. However, an r_m or host kill rate larger than the r_m of the host/prey is not by itself sufficient for natural enemy efficiency, because at low host densities the full potential may not be realized. Then searching efficiency is also of great importance.

(viii) Good density responsiveness (one aspect of searching efficiency) is often said to be an invaluable characteristic of an efficient natural enemy. The natural enemy should be able to locate and reduce pest populations before they have crossed economic threshold densities. Density responsiveness seems to be the most difficult attribute to determine. Firstly, it is not an absolute characteristic, but estimates of this response can only be compared in relation to the estimates for other natural enemies. Secondly, many methods for determining density responsiveness have been proposed but most of them are difficult to apply and do not lead to conclusive answers (van Lenteren, 1986b).

TABLE 2. Criteria for pre-introductory evaluation of natural enemies (after van Lenteren, 1986b)

Criterion	Release programme		
	Seasonal inoculative	Inoculative	Inundative
(i) Seasonal synchronization with host	+	–	–
(ii) Internal synchronization with host	+	+	–
(iii) Climatic adaptation	+	+	+
(iv) No negative effects	+	+	+
(v) Good culture method	–	+	+
(vi) Host specificity	+	–	–
(vii) Great reproductive potential	+	+	–
(viii) Good density responsiveness	+	+	±

+ = Important; – = Not important; ± = Less important

Several of the above criteria are not absolute but have relative values which enable comparison with other natural enemies [criteria (v) to (viii)]. Also, it is very important to consider in what situation the natural enemy will have to function, e.g. will it be applied in usually closed greenhouses in temperate climates, or in generally more "open" protected structures in semi-tropical conditions. In the Mediterranean basin, for example, polyphagous predators like *M. caliginosus* and *Orius* spp. can survive relatively easily even in the absence of the target pest, because alternative prey are present. This allows for early introduction without the risk of extinction of the natural enemy, and for a quick attack of the pest as soon as it occurs.

2.3. *A procedure for selection of natural enemies*

The most relevant studies for pre-introductory evaluation criteria of natural enemies to be used in seasonal inoculative releases and inundative releases are points (ii) to (v) and (vii) of Table 2. In Fig. 3, a flow diagram is presented outlining an evaluation programme. By using such a flow diagram, it is possible to separate useless from potentially useful biological control candidates at an early phase of research. In greenhouse biological control we are not interested in long-term stability *per se*, but merely aim at suppression of pest numbers below the economic threshold. It may suffice to estimate the power of a natural enemy to suppress its host by using system-specific models (van Roermund *et al.*, 1997). First, one would estimate host suppression by natural enemies searching at random. Then conduct simultaneous greenhouses experiments to determine if a natural enemy possesses any characteristics that make it perform better than random searching. Simulation models can indicate whether random searching is sufficient for pest suppression over the growing season. If so, searching efficiency does not have to be measured in more detail, and natural-enemy selection based on determination of r_m or host kill rate will suffice. If random searching is not sufficient, the selection criteria will need to be more rigorous and should include searching efficiency within and between pest patches. Behavioural ecological studies will then be needed to determine which species searches most efficiently.

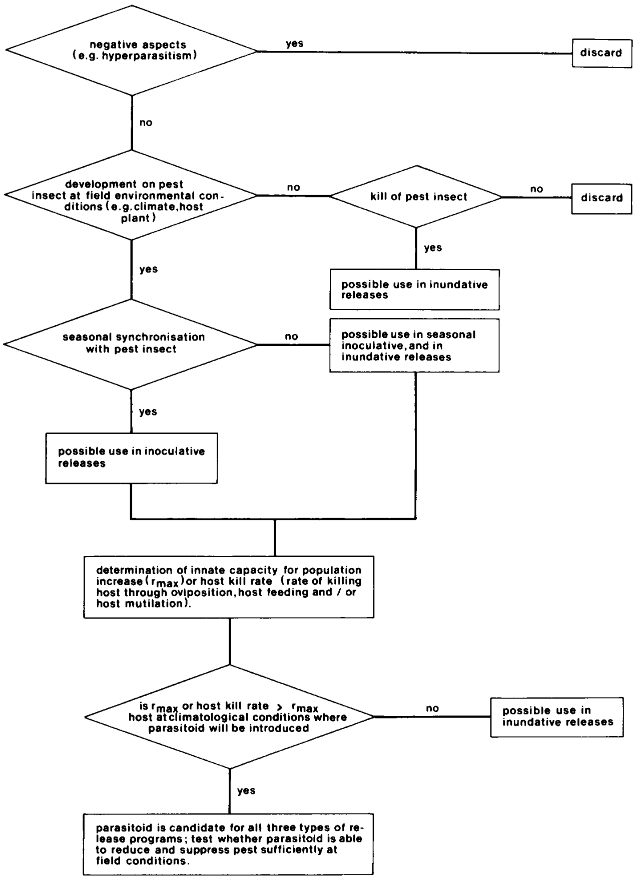


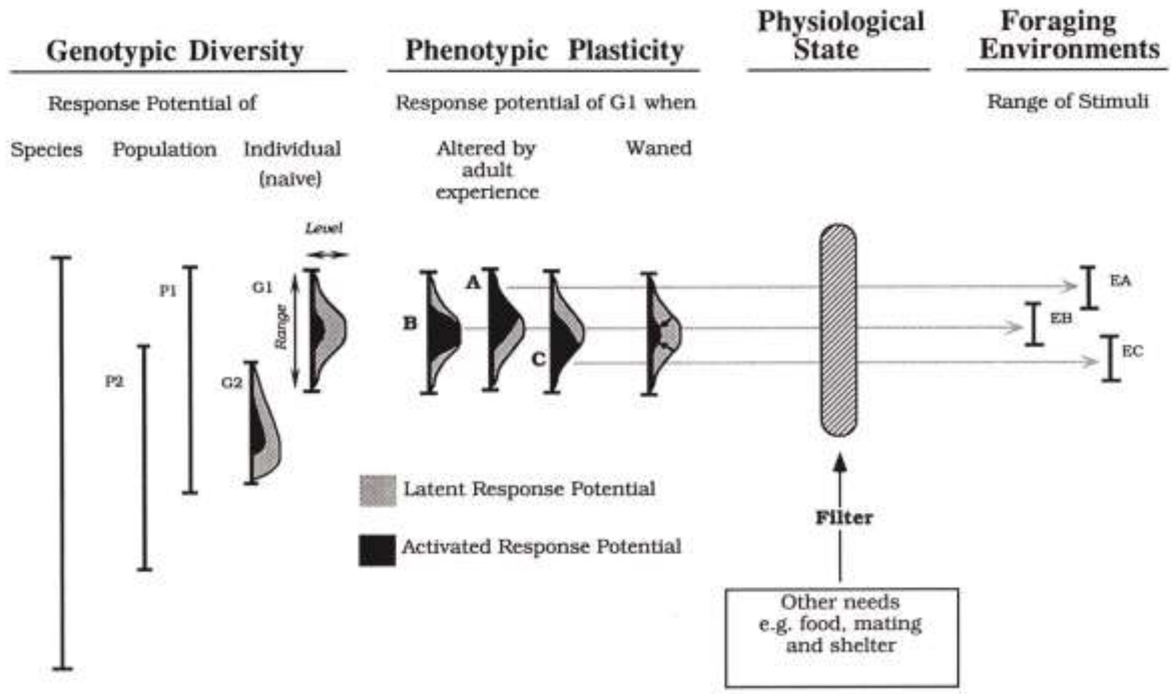
Figure 3. Flow diagram depicting an evaluation programme for natural enemies

The evaluation programme as described here has been used, for example, to select *Trichogramma* species/strains (Pak, 1988), to identify effective parasitoids of leafminers (Minkenberg, 1990), to evaluate natural enemies of aphids (van Steenis, 1995) and whitefly parasitoids (van Roermund, 1995; Drost *et al.*, 1996).

3. Improving the Evaluation and Selection of Natural Enemies

Ecological, genetic and behavioural theory might help to move the more effective biological control agents to the front of the queue of species to be introduced. In particular an understanding of variability in natural enemy behaviour may enhance selection of natural enemies and the targeting of releases. Several papers have discussed how to interpret and deal with variability in natural enemy behaviour (e.g. Lewis *et al.*, 1990; Vet *et al.*, 1990; Vet and Dicke, 1992). Most ecologists are aware that variability in natural enemy behaviour occurs abundantly, often to their despair. It is important to know how natural enemies function in agro-ecosystems, because such understanding may help with the design of systems where natural enemies can play an even more important role in inundative and seasonal inoculative releases.

In this section the sources of variability in behaviour are presented and we will discuss the potential for exploiting this variability to improve biological control.



Variability in foraging behaviour is the result of a complex of factors (from Lewis et al., 1990)

The very core of natural enemy behaviour, host-habitat and host location behaviour shows great variability, and is repeatedly leading to inconsistent results in biological control. Most studies aimed at understanding variability have focused on extrinsic factors as causes for inconsistencies in foraging behaviour. Typically, however, foraging behaviour remained irregular when using precisely the same set of external stimuli. These irregularities are caused by intraspecific, interindividual variation in behaviour. In order to understand erratic behaviour and to manipulate such variation, biological control researchers need to know the origins and breadth of variation. Two types of adaptive variation are distinguished in the foraging behaviour of natural enemies (Lewis *et al.*, 1990):

(i) *Genetically fixed differences* among individuals (fixed-behaviour; innate responses), e.g. natural enemy strains with different capabilities for searching in different habitats, strains with different host acceptance patterns. Such variation is now used in selection of natural enemies. Genetically different strains of the same natural enemy species may react in very different way to the same set of chemical stimuli being emitted by the host/plant complex. Knowledge of such inherited preferences for environments and matching of inherited preferences with stimuli in the environment is of vital importance when choosing correct natural enemy strains. If we want a population of natural enemies to be predictable and consistent in biological control, it must first of all have a proper blend of genetic traits appropriate to the target environment, and traits must occur sufficiently uniformly in the population. This statement has been recognized generally, but has been dealt with only on a gross level in applied programmes (e.g. climate, habitat and host matching).

(ii) *Phenotypic plasticity* (unfixed, learned, plastic behaviour), behavioural adaptation may result from the experience of foraging more effectively in one of the various circumstances that the organism may encounter. Preference develops for foraging in a habitat where suitable hosts were previously encountered. The response of a foraging natural enemy can be quite plastic, can be modified within the bounds of its genetic potential, and is dependent on the individuals experience history. Behavioural modifications can be initiated during pre-imaginal stages and at eclosion, so the response of a "naive" adult will necessarily be routinely altered as a consequence of rearing systems. Such alterations have seldom or never been quantified, although changes in preference have been observed to result from different hosts or host diets. For inundative and seasonal inoculative types of biological control, it is essential to quantify this variability due to learned behaviour. An individual can often change its inherited response range, so it can develop an increased response for particular foraging environments as a result of experience with stimuli of these environments. Absence of reinforcement (i.e. absence of contact with host-related stimuli) will result in a waning of the level of that response and a reversion to the naive preference. Natural enemies are plastic in their behaviour, but operate within genetically defined boundaries.

Only recently have we begun to appreciate the extent to which natural enemies can learn. Many parasitoid species are able to acquire by experience an increased preference for and ability to forage in a particular environmental situation (Vet *et al.*, 1990; Vet and Dicke, 1992). There is some indication for immature learning and abundant evidence for adult learning in natural enemies. Learning is mostly by association. Usually, close range, reliable, unconditional genetically fixed stimuli serve as associators and reinforcers for the longer range, more variable conditional stimuli. Foraging behaviour can continuously be modified according to the foraging circumstances encountered (Vet and Dicke, 1992).

Additionally, foraging behaviour can be strongly influenced by (iii) the *physiological condition* of the natural enemy. Natural enemies face varying situations when meeting their food, mating, reproductive and safety requirements. Presence of strong chemical, visual or auditory cues, cues related to enemy presence, and (temporary) egg depletion can all reduce or disrupt the response to host-foraging cues. For example, hunger may result in increased foraging for food and decreased attention to hosts. In that case, the reaction to food and host cues will be different than when the natural enemy is well fed.

The sources of intrinsic variation in foraging behaviour (genetic, phenotypic and those related to the physiological state) are not mutually exclusive but overlap extensively, even within a singular individual: "The resulting foraging effectiveness of a natural enemy is determined by how well the natural enemy's net intrinsic condition is matched with the foraging environment in which it operates" (Lewis *et al.*, 1990).

How can we manage variability in behaviour of natural enemies? In order to be efficient as biological control agents, natural enemies must be able to: (i) effectively locate and attack a host; and (ii) stay in a host infested area until most/all hosts are attacked. (An "efficient" biological control agent from an anthropocentric point of view, does not necessarily mean efficiency from a natural selection perspective.) Prediction of performance in efficiency is a product of proper matching of intrinsic conditions of the searching natural enemy with the target environments.

Management of the natural enemy component is particularly important in a mass production system especially when they are reared on alternative hosts. In laboratory colonies the natural enemies are removed from the context of natural selection and are exposed to artificial selection for traits not valued in the field (van Lenteren, 1986a). In addition to effects of the genetic component, associative learning may lead to many more changes in behavioural reactions. This, then, results in the need for quality control procedures in the establishment, maintenance and use of natural enemies. Quality control will have to manage both genotypic and phenotypic aspects of behavioural traits. Currently, quality control is applied on a limited scale by mass production units in Europe:

(i) *Genetic qualities.* Successful predation or parasitism of a target host in a confined situation does not guarantee that released individuals will be suitable for controlling the host under field conditions. When selecting among strains of natural enemies, we need to ensure that the traits of the natural enemies are appropriately matched with the targeted use in the field.

(ii) *Phenotypic qualities.* Without care, insectary environments lead to weak or distorted responses. When we understand the sources and mechanism of learning, we can provide the appropriate level of experience before releasing the natural enemies. Also, pre-release exposure to important stimuli can help improve the responses of natural enemies through associated learning, leading to reduction in escape response and increased arrestment in target areas.

(iii) *Physical and physiological qualities.* Natural enemies should be released in a physiological state in which they are most responsive to herbivore or plant stimuli and not be hindered in their response by e.g. food deprivation interfering with searching.

4. From the Laboratory to the Greenhouse and Field: Development of Practical Biological Control

If a candidate natural enemy has been identified in the laboratory, performance testing will have to be done, and, for inundative and seasonal inoculatvive releases, a mass rearing method will have to be developed that results in reliable production of large quantities of agents which are in excellent condition for killing pest organisms, as well as efficient storage, shipment and release methods must be designed (see chapter on Mass Production). After the selection process, the candidate natural enemy is considered as a “product under development”. It is often difficult to determine at this phase how much time will be needed to be able to come up with a commercial product. The next stage is to evaluate the natural enemy under crop production conditions in the greenhouse and the first stage is to perform experimental releases at a range of greenhouse conditions and crop production techniques. The release programme has to be integrated with other crop management practices and evaluation is required of all operations which might interfere with the release and performance of the biological control agent.

The entire process of laboratory and greenhouse of field evaluation is not always performed in the sequential order as described in Section 2. We will present two examples of product development which included a pragmatic element. One programme failed (a parasitoid of Colorado Potato Beetle) and the other one was successful (a predator of thrips).

The egg parasitoid, *Edovum puttleri* Grissell, was evaluated for biological control of Colorado Potato Beetle in Italian greenhouses. Release experiments were carried out in commercial greenhouses before a mass rearing method was developed (Maini *et al.*, 1990). Although greenhouse performance of the parasitoid was satisfactory, it was not commercialized for reasons which included the high costs of mass rearing.

After the accidental introduction of *Frankliniella occidentalis* (Pergande) into Europe, many efforts were made to find natural enemies of this thrips species. Pirate bugs (*Orius* spp.) seemed to be the most widespread and active predators of this species of thrips in Europe. Many researchers and biocontrol companies started to investigate *Orius*, both at laboratory and field level, to determine which species would give acceptable control under the specific conditions found in greenhouses in different areas of Europe. European *Orius* species from different geographic regions were considered [*Orius niger* (Wolff), *Orius laevigatus* (Fieber), *Orius majusculus* (Reuter) and *Orius albidipennis* (Reuter)] (Nicoli and Tommasini, 1996) along with

an exotic, nearctic species [*Orius insidiosus* (Say)] (Dissevelt *et al.*, 1995). Control experiments under practical cropping conditions gave variable results. Therefore, an intensive research programme was started to compare the ability of different species of *Orius* to control thrips in the laboratory and in greenhouses in several greenhouse production areas in Europe (Tommasini and Nicoli, 1993, 1995; Dissevelt *et al.*, 1995; Tommasini *et al.*, 1997). The result of this study was that researchers and biocontrol practitioners concluded that the endemic *O. laevigatus* was the best predator, providing good control under various conditions. *Orius laevigatus* is now the main natural enemy for thrips control in Europe, because it is the best for mass production and performance in greenhouses.

Testing the efficiency of natural enemies under field or greenhouse conditions is complicated and expensive. It is seldom possible to realize the same environmental conditions in several plots, and to obtain the same host plant quality and pest infestation levels. Often, empirical observations lead to the formulation of a practical release programme. Evidence of successful control can, for example, be deduced from situations where, after release of natural enemies, both the pest insect and its natural enemy operate at very low densities and below the economic threshold level (Stehr, 1982). Biocontrol companies usually start field tests by releasing very large numbers of natural enemies to be sure that the control will be satisfactory. The next step is to test different release rates and to determine the lowest release rate resulting in reliable control. Scientifically, this type of testing should preferably be done in a situation where other species of natural enemies do not interfere, and field testing can then only be done in screencages. The release rates will have to be adapted to the production method of the crop and the region where it is produced. For greenhouses, in situations with low pest immigration from outside (for example in winter in northern Europe when greenhouses are closed) one or a few releases of the natural enemy may suffice. In Mediterranean areas, with open greenhouses, releases may have to continue throughout the growing season. Practical release schemes are continuously modified based on greenhouse experiences, and it normally takes several years before a standard release programme is available. Scientifically designed and statistically reliable experimentation to determine the efficiency of different natural enemies of the same pest organisms has seldom been performed because of prohibitive costs.

Candidate natural enemies may be tried out on a small scale even if the laboratory development process has not yet been completed. Trials under practical conditions will provide information about how the natural enemy can be integrated with other components of pest and disease control and information for development of practical release programmes. Such trials are conducted on properties of “pioneer” growers who like to try out new developments. For a critical discussion of this topic, see van Lenteren (2006).

During the whole process of product development, a biocontrol company will keep an eye on the cost-effectiveness of the new product. When mass production, shipment and release of a specific natural enemy are expensive, it might be realistic to advise it for release only in ornamentals or the more expensive vegetables, where higher investments for pest control are normally made. Sometimes the high costs of mass rearing has resulted in release of low (even too low) numbers of natural enemies, with the risk of unreliable results and negative advertisement for biological control. The costs of a natural enemy may even determine the type of release programmes. A very cheap natural enemy can be used in blind, regular, inundative

Dacnusa sibirica

releases without monitoring of the pest. A more expensive natural enemy is better used in well planned, seasonal inoculative releases after the pest has been detected. When two natural enemies are available for control of the same pest, the ultimate choice may be based on very practical considerations, not just the level of performance and costs of each species. An example is the use of the parasitoid *Diglyhpus isaea* for the control of leafminers instead of the parasitoid *Dacnusa sibirica* Telenga, the control effect of the ectoparasitoid *Diglyphus* is much easier to detect in the field by the grower or advisor than that of the endoparasitoid *Dacnusa*.

Once a release programme has been developed, it will have to be modified regularly, because new plant cultivars may be used, growing conditions may change, other pests and pesticides may be used in the system, etc. It is important to realize that development of biological and integrated control is knowledge intensive and that these systems may need regular modification.

5. Importation and Release of Exotic Natural Enemies

Quite a number of the natural enemies used for biological control of pests in Europe are exotic organisms (for an overview, see van Lenteren, 1997). Because each organism may become established, extreme care should be exerted during the evaluation phase to prevent escapes. This is always important, whether the organism is being introduced into a new region or developed for inundative or inoculative releases. Until now, introductions of several hundreds of species of insect natural enemies have seldomly led to environmental problems. Any future problems can to a large extent be avoided by following the procedures of selection, importation and release as described above.

The use of biological control of insect pests has considerably increased during the past decades as it provides an environmentally attractive alternative to chemical pest control. Surprisingly, however, biological control practitioners are nowadays confronted with criticism from environmentalists because of the fear that the biocontrol agents may attack: (i) beneficial non-target organism like pollinators or other natural enemies; (ii) rare or endangered insects like butterflies; or (iii) other non-target organisms. Such undesirable influences on ecosystems have not, in fact, been observed, but it should be realized that the effect of biocontrol introductions on the native fauna has rarely been studied in great detail. The types of risks resulting from biological control introductions have been classified as: (i) direct effects leading to extinction or reduction in numbers of native non-target organisms; and (ii) indirect effects such as preying on or parasitizing indigenous natural enemies or competition for hosts or prey with indigenous natural enemies.

The literature of the past 100 years on introductions of natural enemies for insect control has provided no evidence of extinction of species as a consequence of such introductions, and the generally strong preference for the introduction of highly specific natural enemies may explain this. Reduction in populations of native non-target organisms is difficult to demonstrate. It is very important to realize that ecologists have long recognized the role of predators, parasitoids and pathogens in regulating populations of plant-eating organisms (in agro-ecosystems often pest insects), thereby keeping the world green. In natural and agricultural ecosystems, many herbivores occur at extremely low densities because of the action of natural enemies. Also the natural enemies themselves are normally rare when herbivores occur at low numbers. However, for each herbivore species, many different species of natural enemies may occur at such low densities without eradication of either the herbivore or its natural enemies.

Because of the demands from conservationists, there is now a tendency in some European countries to avoid all possible risks and to refuse permission for importation and release of biological control agents, or to overregulate importations. Both measures seriously hamper further development of biological control. Long before governmental demands, biological control workers themselves have developed risk assessment procedures which are based on taxonomic status and biology of natural enemy, safety screening on other organisms, and evaluation of host specificity. Such data, combined with an environmental risk analysis of other control methods, can be made to make informed decisions to choose between biological control or other control methods (for a more extensive discussion of this topic, see chapter on environmental risk analysis).

6. Conclusions

Several current trends will stimulate the application of biological control. Firstly, fewer new insecticides are becoming available because of skyrocketing costs for development and registration. Secondly, pests continue to develop resistance to any type of pesticides (conventional and high-tech modern ones), a problem particularly prevalent in greenhouses, where intensive management and repeated pesticide applications exert strong selective pressure on pest organisms. Thirdly, there is a strong demand from the general public (and in an increasing number of countries also from parliament) to reduce the use of pesticides.


By Patricia C. Matteson

The "50% Pesticide Cuts" in Europe:

A Glimpse of Our Future?

Because of the desire to reduce pesticide use, the future role of biological control is expected to increase strongly. This is aided by the extensive demonstration of its positive role and because many new natural enemy species still await discovery. Cost/benefit analyses show that biological control is the most cost effective control method (van Lenteren, 1993). With the improved methods of evaluation and an increased insight into the functioning of natural enemies, the cost effectiveness may even be increased.

We should not expect that biological control will completely replace chemical control. Biological control is a powerful option and can be applied to a much larger area than at present. Biological control should be used in IPM programmes where it is combined with other pest control methods, including very careful use of certain types of chemical control. A benefit for pesticides from increased use of biological control is that this may result in extended use of chemical products because of slower development of resistance. In order to serve agriculture as well as the environment and human health, we should harvest the best from all control methods to develop effective IPM programmes.

References

Alomar, O., Goula, M. and Albajes, R. (1994) Mirid bugs for biological control: Identification, survey in non-cultivated winter plants, and colonization of tomato fields, *IOBC/WPRS Bulletin* **17**(5), 217–223.

Arzone, A., Alma, A. and Tavella, L. (1990) Ruolo dei Miridi (Rhynchota, Hetereoptera) nella limitazione di *Trialeurodes vaporariorum* Westw. (Homoptera, Aleyrodidae), *Bollettino di Zoologia Agraria e di Bachicoltura, Ser. II* **22**(1), 43–51.

Calabretta, C., Calabro, M., Colombo, A. and Campo, G. (1995) Diffusione di *Liriomyza huidobrensis* (Blanchard) (Diptera, Agromyzidae) in colture protette della Sicilia, *Informatore Fitopatologico* **45**(6), 24–30.

Celli, G., Benuzzi, M., Maini, S., Manzaroli, G., Antoniacci, L. and Nicoli, G. (1991) Biological and integrated control in protected crops of northern Italy's Po Valley: Overview and outlook, *IOBC/WPRS Bulletin* **14**(5), 2–12.

DeBach, P. and Rosen, D. (1991) *Biological Control by Natural Enemies*, Cambridge University Press, Cambridge.

Dissevelt, M., Altena, K. and Ravensberg, W.J. (1995) Comparison of different *Orius* species for control of *Frankliniella occidentalis* in glasshouse vegetable crops in the Netherlands, *Medelingen – Faculteit Landbouwkundige en Toegepaste Biologische Wetenschappen, Universiteit Gent* **60**(3a), 839–845.

Drost, Y.C., Fadl Elmula, A., Posthuma-Doodeman, C.J.A.M. and van Lenteren, J.C. (1996) Development of selection criteria for natural enemies in biological control: Parasitoids of *Bemisia argentifolii*, *Proceedings of the Section Experimental and Applied Entomology of the Netherlands Entomological Society* **7**, 165–170.

Huffaker, C.B. and Messenger, P.S. (eds.) (1976) *Theory and Practice of Biological Control*, Academic Press, New York.

Lewis, W.J., Vet, L.E.M., Tumlinson, J.H., van Lenteren, J.C. and Papaj, D.R. (1990) Variations in parasitoid foraging behaviour: Essential elements of a sound biological control theory, *Environmental Entomology* **19**, 1183–1193.

Mackauer, M., Ehler, L.E. and Roland, J. (eds.) (1990) *Critical Issues in Biological Control*, Intercept, Andover.

Maini, S., Nicoli, G. and Manzaroli, G. (1990) Evaluation of the egg parasitoid *Edovum putleri* Grissel (Hym.: Eulophidae) for biological control of *Leptinotarsa decemlineata* (Say) (Col.: Chrysomelidae) on eggplant, *Bollettino dell'Istituto di Entomologia "Guido Grandi" della Universita degli Studi di Bologna* **44**, 161–168.

Minkenberg, O.P.J.M. (1990) On seasonal inoculative biological control, PhD Thesis, Wageningen Agricultural University.

Nicoli, G. and Tommasini, M.G. (1996) *Orius laevigatus*, *Informatore Fitopatologico* **46**(7), 21–26.

Pak, G.A. (1988) Selection of *Trichogramma* for inundative biological control, PhD Thesis, Wageningen Agricultural University.

Parrella, M.P. (1990) Biological control in ornamentals: Status and perspectives, *IOBC/WPRS Bulletin* **13**(5), 161–168.

Stehr, F.W. (1982) Parasitoids and predators in pest management, in R.L. Metcalf and W.H. Luckman (eds.), *Introduction to Insect Pest Management*, Wiley-Interscience, New York, pp. 135–173.

Tommasini, M.G., Maini, S. and Nicoli, G. (1997) Advances in the integrated pest management in protected eggplant crops by seasonal inoculative releases of *Orius laevigatus*, *Advances in Horticultural Science* **11**, 182–188.

Tommasini, M.G. and Nicoli, G. (1993) Adult activity of four Orius species reared on two preys, *IOBC/WPRS Bulletin* **16**(2), 181–184.

Tommasini, M.G. and Nicoli, G. (1996) Evaluation of *Orius* spp. as biological control agents of thrips pests: Further experiments on the existence of diapause in *Orius laevigatus*, *IOBC/WPRS Bulletin* **19**(1), 183–186.

van Lenteren, J.C. (1986a) Evaluation, mass production, quality control and release of entomophagous insects, in J.M. Franz (ed.), *Biological Plant and Health Protection*, Fischer, Stuttgart, pp. 31–56.

van Lenteren, J.C. (1986b) Parasitoids in the greenhouse: Successes with seasonal inoculative release systems, in J.K. Waage and D.J. Greathead (eds.), *Insect Parasitoids*, Academic Press, London, pp. 341–374.

van Lenteren, J.C. (1993) Parasites and predators play a paramount role in pest management, in R.D. Lumsden and J.L. Vaughn (eds.), *Pest Management: Biologically Based Technologies*, American Chemical Society, Washington, DC, pp. 66–81.

van Lenteren, J.C. (1997) Benefits and risks of introducing exotic macro-biological control agents into Europe, *Bulletin OEPP/EPPO* **27**, 15–27.

Lenteren, J.C. van, 2006. How not to evaluate augmentative biological control. Biological Control 39: 115-118.

van Lenteren, J.C. and Woets, J. (1988) Biological and integrated pest control in greenhouses, *Annual Review of Entomology* **33**, 239–269.

van Roermund, H.J.W. (1995) Understanding biological control of greenhouse whitefly with the parasitoid *Encarsia formosa*: From individual behaviour to population dynamics, PhD Thesis, Wageningen Agricultural University.

van Roermund, H.J.W., van Lenteren, J.C. and Rabbinge, R. (1997) Biological control of greenhouse whitefly with the parasitoid *Encarsia formosa* on tomato: An individual-based simulation approach, *Biological Control* **9**, 25–47.

van Steenis, M. (1995) Evaluation and application of parasitoids for biological control of *Aphis gossypii* in glasshouse cucumber crops, PhD Thesis, Wageningen Agricultural University.

Vet, L.E.M. and Dicke, M. (1992) Ecology of infochemical use by natural enemies in a tritrophic context, *Annual Review of Entomology* **37**, 141–172.

Vet, L.E.M., Lewis, W.J., Papaj, D.R. and van Lenteren, J.C. (1990) A variable-response model for parasitoid foraging behaviour, *J. of Insect Behavior* **3**, 471–490.

9. Mass production, storage, shipment and release of natural enemies.

Latest paper on natural enemies used in commercial augmentative biological can be downloade for free at: http://www.springerlink.com/content/b3r301232kr7251h/fulltext.pdf

The material of this chapter is based largely on Lenteren, J.C. van (ed.), 2003a. Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. CABI Publishing, Wallingford, UK: 327 pp; Chapter 12, van Lenteren & Tommasini, 2003: 181-189.

Mass production

Since the beginning of the 20th century mass production of natural enemies has been considered as a means of improving biological control programmes, especially those based on inundative and seasonal inoculative releases. For general information on mass production of arthropods, we refer to Morrison and King (1977), King and Morrison (1984), Singh (1984), Singh and Moore (1985), van Lenteren (1986a; 2003). For mass production related to commercially produced natural enemies, we refer to van Lenteren (1986b), van Lenteren and Woets (1988), and Bolckmans (1999). We will not discuss the question on how to obtain a good stock colony to start a mass production. This issue is, among others, addressed by van Lenteren (2003b), Nunney (2003) and Hoekstra (2003). In this section we will briefly summarise developments in mass rearing of natural enemies for commercial biological control during the 20th Century.

Mass production of beneficials is a "skillful and highly defined processing of an entomophagous species through insectary procedures which results in economical production of millions of beneficial insects" (Finney and Fisher, 1964). This is true for most of the mass-rearing programmes, but there are important exceptions where mass production seems to be a fairly simple process.

The first step in a mass-rearing programme is a trial to rear the natural enemy on a natural host (the pest organism) in an economical way. Most of the natural enemies are reared in this way. However, several natural enemies are not mass reared on their natural host because it is either too expensive or undesirable due to the risk of infection with the pest organism or concurrent infection with other pests or diseases when natural enemies are released on their natural substrate. In these cases a search is made for an opportunity to rear the natural enemy on alternative host (and often an alternative host plant).

A subsequent step in making mass rearing more economical is to change from a natural host medium (host plant) to an artificial medium for rearing the host. Rearing insects on artificial diets was developed earlier this century and considerable progress has been made recently. Rearing on artificial diets is considerably cheaper as less expensively climatized space is needed, but artificial rearing may create serious quality problems, which will be discussed later in this chapter. Singh (1984) summarises the historical development, recent advances and future prospects for insect diets as follows:

1. some 750 species, mainly phytophagous insects can be reared successfully on (semi-) artificial diets,
2. only about two dozen species have been successfully reared for several generations on completely artificial diets,
3. large scale mass rearing on artificial media has been developed for less than twenty species of insects,
4. quality control is essential, as there can be dietary effects on all critical performance traits of the mass-reared insect and also on the natural enemy produced on a host that was mass reared on an artificial medium, and

5. suitable bioassays are important for answering the question "what is the ultimate effect of the diet on the reared insect?"

A final step when trying to minimise rearing costs is the search for ways to rear the natural enemy on an artificial diet. This has been attained for several ecto- and endoparasitoids (e.g. *Trichogramma*) and a few predators (e.g. *Chrysoperla*). The technology for rearing natural enemies on diets is, however, far less developed than that for rearing of pest species (see chapter on Artificial Rearing; see website IOBC Global under Working Group Artificial Mass Rearing and Quality Control; Grenier & DeClercq, 2003; De Clercq, 2004).

The fast development of commercial biological control based on mass produced natural enemies can be illustrated well with data from Europe. About 150 species of natural enemies have been imported and released into Europe during the 20th Century to control about 55 mite and insect pest species. Until 1970 this mainly concerned inoculative (classical) biological control. After 1970 many developments took place in greenhouses and annual field crops, and commercial biological control programmes for circa 50 pest species were developed by importing more than 60 species of natural enemies. In addition, more than 40 endemic species of natural enemies were employed in commercial biological control. For all these species, fine-tuned mass production systems had to be developed. An overview of about 125 species of natural enemies that are commercially available is given in the table below.

Our experience with the development of new biological control programmes has shown that dogmatism is useless when selecting natural enemies. This contrasts with the approach of earlier biocontrol workers (see e.g. DeBach, 1964). We have, for example, had excellent control results by releasing endemic natural enemies against exotic pests and vice versa: all combinations are worth trying (for data, see van Lenteren & Tommasini, 2003).

Storage of natural enemies

It is necessary to have storage methods and facilities available to meet the requirements for good planning for a mass production unit and because of the difficulty of accurately predicting demand from clients (both delivery dates and quantities). This is relatively simple for microbial biocontrol agents like fungi, viruses and bacteria because they can often be stored in a resting stage for months or even years. Many predators and parasitoids can only be stored for a short time. This usually involves placing the natural enemies as immatures at temperatures between 4 and 15 ^{o}C. Normally, storage only lasts several weeks, but even then reduction in fitness is the rule. The pupal stage seems to be most suitable for short-term storage.

Data on long-term storage of natural enemies or their hosts are limited. Host material (e.g. eggs of *Sitotroga cerealella* and *Grapholita lineatum*) stored for long periods (in the case of *Grapholita* for up to 5 years) in liquid nitrogen could still be used for production of *Trichogramma* and *Trissolcus simoni* respectively. Eggs of *Ephestia kuehniella* can be sterilised by UV radiation or freezing, and then be stored at low temperature for several months without losing their value as alternative food for mass production of predators such as *Chrysoperla* and *Orius*. The parasitoid *Diglyphus isaea* can be stored at a low temperature for at least two months during which time mortality does not increase and fecundity remains the same. Hagvar and Hofsvang (1991) reported that some species of Aphidiidae (e.g. *Aphidius matricariae*) can be stored at low temperatures for several weeks.

The possibility of storing beneficials in the diapausing stage has been studied, but most of this work has not yet led to practical application, because unacceptably high mortality occurred during the artificially induced diapause. There are, however, some positive exceptions. Diapausing adults of the predator *Chrysoperla carnea* can be stored at a low temperature for about 30 weeks while maintaining an acceptable level of survival and reproduction activity (Tauber *et al.*, 1993). Also the predator *Orius insidiosus* maintains good longevity and reproduction rate after storage in diapause for up to 8 weeks (Ruberson *et al.*, 1998). The predator *Aphidoletes aphidimyza* can survive periods of 3 to 8 months when stored at 10^{o}C (Tiitanen, 1988). Long-term storage of the diapausing stage of the parasitoid *Trichogramma*, has been successful for periods up to a year, and is now commercially exploited (J. Frandon, Biotop, Antibes, France, 1996, personal communication).

Long-term storage capability is very desirable for production companies, because:

- continuous production of the same quantity of beneficial insects is often economically more attractive than seasonal production of very large numbers
- storage facilities enables them to build up reserve supplies of entomophages to compensate for periods of low production or periods of unexpected high demands
- storage makes rearing possible at the best period of the year, e.g. at a period that host plants can be grown under optimal conditions.

Collection and shipment of natural enemies

After production, the beneficials should be delivered to the growers as soon as possible. If delivery is looked after by the producer and occurs within 48 hours after harvesting the organisms, no special shipment procedures are normally needed for parasitoids and non-cannibalistic predators other than protection against excessive heat, cold or rough handling. When transport takes several days, climatized containers should be used and it may be necessary to add food (e.g. honey in the case of parasitoids and pollen / prey for predators). A way to overcome problems with long times for transport of predators, young stages can be packaged with food so that further development takes place during transport. Packaging of predators demands special attention when cannibalism is a common phenomenon. Many of the commercially available predators are generalists and exhibit cannibalism when kept at high densities, even if food is available in the containers for shipment. To reduce the risk of cannibalism, it is common to provide hiding places for the natural enemy by using paper, buckwheat, vermiculite or wheat bran in the container (for an overview of shipment methods, see van Lenteren & Tommasini, 2003). In the early days of mass production the biological control agents were often collected and shipped on the host plant on which they were reared. With the internationalisation of biocontrol, shipment on or in inert media became a necessity. Ingenious collection and shipping procedures have been developed.

Poor shipping conditions frequently led to natural enemies arriving either dead or in poor condition. Difficulties in shipping can be considerable in countries where crops with the same target pest are not concentrated together and where distances are large. Most transport is still by truck, although an increasing quantity is sent by aircraft. With intercontinental transport problems are caused less by containerisation than by the sometimes excessively long handling time at customs which leads to high mortality or decrease in fitness. Logistics of shipments remains one of the main problems for the commercialisation of biological control. Examples of the different techniques for collecting, counting, packaging and shipping of the natural enemies can be found in van Lenteren & Tommasini (2003).

Release of natural enemies

Developmental stage at which organism is released

Entomophagous insects can be brought into greenhouses or the field in different stages of their development (for an overview of release methods, see van Lenteren & Tommasini, 2003):

- eggs (e.g. *Chrysoperla*)
- larvae or nymphs (e.g. *Chrysoperla, Phytoseiulus, Amblyseius, Orius*)
- pupae or mummies (e.g. *Aphidius, Trichogramma, Encarsia*)
- adults (e.g. *Dacnusa, Diglyphus, Orius, Phytoseiulus*)
- all stages together (e.g. *Phytoseiulus, Amblyseius*)

The stage in which the beneficials are introduced depends mainly on the ease of transport and manipulation in the field, but it is - of course - also important to release the natural enemy at a stage which is most active at killing the pest. Usually the stage which is least vulnerable to mechanical handling is chosen and therefore a none-mobile stage, often the egg or pupa, is most suited for transport and release. In situations where it is difficult, but essential, to distinguish the natural enemy from the pest, the only solution is to introduce adults. Adult releases for parasitoids are advised only when younger natural enemy stages cannot be distinguished or separated from the pest insect: handling and releasing of delicate adult parasitoids is very difficult and often a large reduction of fertility is observed compared to the fertility of parasitoids when released as immatures. When the natural enemy is released in one of the developmental stages which do not predate or parasitise the host, the timing should be such that the active stage emerges at the right moment of pest population development. For some natural enemies the stage of release depends on pest development: when pest density is low, release of first instar *C. carnea* suffices, when the infestation with the pest organisms is already relatively high, it is better to release second instar larvae, which have a much higher predation capacity.

Methods of introduction

Beneficials are introduced into the field in many ways (van Lenteren & Tommasini, 2003). Eggs and pupae are either distributed over the field on their normal substrate (leaves of the host plant, e.g. *Chrysoperla* and *Encarsia*) or glued on paper/cardboard cards (e.g. *Encarsia*, *Trichogramma*). These stages of the natural enemies can also be collected, and put into containers, which are then brought into the field (e.g. *Trichogramma*).

The mobile stages of natural enemies, larvae or nymphs and adults, can be put into the field in containers from which they emerge (e.g. many adult parasitoids and predators) or the grower can distribute natural enemies in these stages over the crop for example by "sprinkling" them onto the plant. In this case, the use of dispersal material (e.g. buckwheat, vermiculite) is often necessary in order to obtain a homogeneous distribution of small natural enemies. When natural substrates (e.g. buckwheat or wheat bran) are used as dispersal materials, they must be free from pesticides.

Instead of introducing the predator or parasitoid by itself one can also introduce a whole "production unit": e.g. "banker-plants" containing the host insect and its natural enemy can be brought into a crop. When the introduced host population is almost exterminated, the natural enemies invade the surrounding crop.

The moment of introduction

In many cases the natural enemies are released when the pest organism has been observed, although it is not unusual to apply "blind releases" when sampling of the pest is difficult (e.g. whiteflies) or when pest populations develop very quickly like those of aphids and thrips. When pest generations are not yet overlapping early in the growing season, proper timing of the release(s) is essential so that the beneficials are available when the preferred host stages are present.

Determining the dosage, the distribution and the frequency of the releases are very difficult problems, which are encountered, in both inundative and seasonal inoculative release programmes. Release ratios are not critical in inundative release programmes as long as it is possible to release a (super)abundance of natural enemies. This, however, may be limited by the cost of mass production. In seasonal inoculative programmes release ratios are more critical: if too few beneficials are released effective control will be obtained after the pest has caused economic damage. If too many are released there is a risk of exterminating the pest and thus eventually also of the natural enemy. This is a practical problem in small tunnels and greenhouses. In the latter situation resurgence of the pest is likely and a serious threat. In these seasonal innoculative release programmes the release ratios are usually determined by trial and error.

Conclusions

Mass production of natural enemies has seen a very fast development during the past three decades: the numbers produced have greatly increased, the spectrum of species available has widened dramatically, and mass production methods clearly have evolved. Developments in the area of mass production, quality control, storage, shipment and release of natural enemies have decreased production costs and led to better product quality, but much more can be done. Innovations in long-term storage (e.g. through diapause), shipment and release methods may lead to a further increase in natural enemy quality with a concurrent reduction in costs of biological control, thereby making it easier and more economical to apply.

References

Bolckmans, K.J.F, 1999. Commercial aspects of biological pest control. In: Albajes, R., Gullino, M.L., van Lenteren, J.C. and Elad, Y. (eds.) *Integrated Pest and Disease Management in Greenhouse Crops*. Kluwer Academic Publishers, Dordrecht: pp. 310-318.

DeBach, P. (ed.) (1964) *Biological Control of Insect Pests and Weeds.* Chapman and Hall, London, 844 pp.

De Clercq, P. (2004). Culture of natural enemies on factitious foods and artificial diets. *In:* Encyclopedia of Entomology (J. L. Capinera, Ed.). Kluwer Academic Publishers, Dordrecht, vol. I, 650-652.Finney, G.L. and Fisher, T.W. (1964) Culture of entomophagous insects and their hosts. In DeBach, P. (ed.), *Biological Control of Insect Pests and Weeds*. Chapman and Hall, London, pp. 329-355.

Grenier, S. and P. DeClercq 2003. Comparison of Artificially vs. Naturally Reared Natural Enemies and Their Potential for Use in Biological Control. Chapter 9 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 115-131.

Hoekstra, R.F., 2003. Adaptive Recovery of Fitness Reduction: the Role of Population Size, 89-92

Hagvar, E.B. and Hofsvang, T. (1991) Aphid parasitoids (Hymenoptera: Aphidiidae): biology, host selection and use in biological control. *Biocontrol News and Information* 12, 13-41.

King, E.G. and Morrison, R.K. (1984) Some systems for production of eight entomophagous arthropods. In: King, E.G. and Leppla, N.C. (eds.) *Advances and Challenges in Insect Rearing*. USDA/ARS, New Orleans, pp. 206-222.

Lenteren, J.C. van (1986a) Evaluation, mass production, quality control and release of entomophagous insects. In: Franz, J.M. (ed.) *Biological Plant and Health Protection*. Fischer, Stuttgart, pp. 31-56.

Lenteren, J.C. van (1986b) Parasitoids in the greenhouse: successes with seasonal inoculative release systems. In: Waage, J.K. and Greathead, D.J. (eds.) *Insect Parasitoids*. Academic Press, London, pp. 341-374.

Lenteren, J.C. van and Woets, J. (1988) Biological and integrated control in greenhouses. *Annual Review of Entomology* 33, 239-269.

Lenteren, J.C. van (ed.), 2003a. Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. CABI Publishing, Wallingford, UK: 327 pp.

Lenteren, J.C. van, 2003b. Need of quality control of mass-produced biological control agents. Chapter 1 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 1-18.

Lenteren, J.C. van & M.G. Tommasini, 2003. Mass Production, Storage, Shipment and Release of Natural Enemies. Chapter 12 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 181-189.

Morrison, R.K. and King, E.G. (1977) Mass production of natural enemies. In: Ridgway, R.L. and Vinson, S.B. (eds.) *Biological Control by Aumentation of Natural Enemies*. Plenum, New York, pp. 183-217.

Nunney, L. 2003. Managing Captive Populations for Release: a Population-genetic Perspective, 73-87

Ruberson, J.R., Kring, T.J. and Elkassabany, N., (1998) Overwintering and diapause syndrome of predatory Heteroptera. In: Coll, M. and Ruberson, J.R. (eds.) *Predatory Heteroptera: their ecology and use in biological control*. Thomas Say Publications in Entomology, ESA, Lanham, Maryland: pp. 49-69

Singh, P. (1984) Insect diets. Historical developments, recent advances, and future prospects. In: King, E.G. and Leppla, N.C. (eds.) *Advances and Challenges in Insect Rearing*. USDA/ARS, New Orleans, pp. 32-44.

Singh, P. and Moore, R.F. (eds.) (1985) *Handbook of Insect Rearing*. Elsevier, Amsterdam, Volume 1, 488 pp., Volume 2, 514 pp.

Tauber, M.J., Tauber, C.A. and Gardescu, S. (1993) Prolonged storage of *Chrysoperla carnea* (Neuroptera: Chrysopidae). *Environmental Entomology* 22, 843-848.
Tiitanen, K. (1988) Utilization of diapause in mass production of *Aphidoletes aphidimyza* (Rond.) (Dipt., Cecidomyiidae). *Annales Agriculturae Fenniae* 27, 339-343.

Table 1. Commercially available natural enemies (parasitic insects, predatory insects, predatory mites, and entomopathogenic nematodes, fungi, bacteria and viruses) of insects, mites and other evertebrate pests in Europe (situation in the year 2000; after van Lenteren, 2003)

Natural enemy (endemic / exotic)	Pest (endemic / exotic)	In use since
**Adalia bipunctata* (en)	*Toxoptera aurantii* (en)	1998
**Adoxophyes orana* granulosis virus (en)	*Adoxophyes orana* (en)	1995
**Aleochara bilineata* (en)	*Delia* root flies (en)	1995
Amblyseius barkeri (en)	*Thrips tabaci* (en)	1981
	Frankliniella occidentalis (ex)	1986
Amblyseius (Neioseiulus) degenerans (ex)	Thrips (en, ex)	1993
Amblyseius fallacis (ex)	Mites (ex)	1997
**Amblyseius largoensis* (ex)	Mites (ex)	1995
**Amblyseius lymonicus* (ex)	Thrips (en, ex)	1997
**Ampulex compressa* (ex)	Blattidae (en, ex)	1990
**Anthocoris nemorum* (en)	Thrips (en, ex)	1992
**Anagrus atomus* (en)	Cicadellidae (en, ex)	1990
**Anagyrus fusciventris* (ex)	Pseudococcidae (en,ex)	1995
**Anagyrus pseudococci* (en)	Pseudococcidae (en,ex)	1995
Aphelinus abdominalis (en)	*Macrosiphum euphorbiae* (en)	1992
	Aulacorthum solani (en)	1992
**Aphelinus mali* (ex)	*Eriosoma lanigerum* (ex)	1980
Aphidoletes aphidimyza (en)	Aphids (en, ex)	1989
Aphidius colemani (ex)	*Aphis gossypii, M. persicae* (ex, en)	1992
Aphidius ervi (en)	*Macrosiphum euphorbiae* (en)	1996
	Aulacorthum solani (en)	1996
Aphidius matricariae (en)	*Myzus persicae* (en)	1990
**Aphidius urticae* (en)	*Aulacorthum solani* (en)	1990
**Aphytis holoxanthus* (ex)	Diaspididae (ex)	1996
**Aphytis melinus* (ex)	Diaspididae (en, ex)	1985
**Aprostocetus hagenowii* (ex)	Blattidae (en, ex)	1990
Bacillus thuringiensis (en, ex)	Lepidoptera (en, ex)	1972
Beauveria brongniartii (en)	*Melolontha* (en)	1985
**Bracon hebetor* (ex)	Lepidoptera (en)	1980
**Cales noacki* (ex)	*Aleurothrixus floccosus* (ex)	1970
**Chilocorus baileyi* (ex)	Diaspididae (en, ex)	1992
**Chilocorus circumdatus* (ex)	Diaspididae (en, ex)	1992
**Chilocorus nigritus* (ex)	Diaspididae, Asterolecaniidae (en, ex)	1985
**Chrysoperla carnea* (en, ex)	Aphids (en, ex) and others	1987
**Chrysoperla rufilabris* (ex)	Aphids (en, ex) and others	1987
**Clitostethus arcuatus* (en)	Aleyrodidae	1997
**Coccinella septempunctata* (en)	Aphids (en)	1980
**Coccophagus lycimnia* (ex)	Coccidae (en, ex)	1988
**Coccophagus rusti* (ex)	Coccidae (en, ex)	1988
**Coccophagus scutellaris* (en)	Coccidae (en, ex)	1986
**Coenosia attenuata* (en)	Diptera (en), Sciaridae (en)	1996
	Agromyzidae (en, ex), Aleurodidae (ex)	1996

**Comperiella bifasciata* (ex)	Diaspididae (ex)	1985
**Cryptolaemus montrouzieri* (ex)	Pseudococcidae, Coccidae (en,ex),	
	Planococcus citri (ex)	1992
**Cydia pomonella* granulosis virus (en)	*Cydia pomonella* (in)	1995
Dacnusa sibirica (en)	*Liriomyza bryoniae* (en)	1981
	Liriomyza trifolii (ex)	1981
	Liriomyza huidobrensis (ex)	1990
Delphastus pusillus (ex)	*Trialeurodes vaporariorum* (ex)	1993
	Bemisia tabaci/argentifolii (ex)	1993
Dicyphus tamaninii (en)	Whitflies (ex), thrips (en, ex)	1996
Diglyphus isaea (en)	*Liriomyza bryoniae* (en)	1984
	Liriomyza trifolii (ex)	1984
	Liriomyza huidobrensis (ex)	1990
**Diomus* spec. (ex)	*Phenacoccus manihoti* (ex)	1990
**Encarsia citrina* (ex)	Diaspididae (en, ex)	1984
Encarsia formosa (ex)	*Trialeurodes vaporariorum* (ex)	1970 (1926)
	Bemisia tabaci/argentifolii (ex)	1988
Encarsia tricolor (en)	*Trialeurodes vaporariorum* (ex)	1985
**Encyrtus infelix* (ex)	Coccidae (en, ex)	1990
**Encyrtus lecaniorum* (en)	Coccidae (en, ex)	1985
**Episyrphus balteatus* (en)	Aphids (en, ex)	1990
Eretmocerus californicus (ex)	*Bemisia tabaci/argentifolii* (ex)	1995
Eretmocerus mundus (en)	*Bemisia tabaci/argentifolii* (ex)	1995
**Franklinothrips vespiformis* (ex)	Thrips (ex)	1990
**Gyranusoidea* spp. (ex)	Pseudococcidae (en, ex)	1990
**Harmonia axyridis* (ex)	Aphids (en)	1995
Heterorhabditis bacteriophora	*Otiorrhynchus sulcatus* and other spp. (en)	1984
Heterorhabditis megidis and other spp. (en, ex)	*Otiorrhynchus sulcatus* and other spp. (en)	1984
**Hippodamia convergens* (ex)	Aphids (en, ex)	1993
**Hungariella peregrina* (ex)	Pseudococcidae (en, ex)	1990
**Hypoaspis aculeifer* (en)	Sciaridae, *Rhizoglyphus echinopus* (en)	1996
	Rhizoglyphus rolini (en), Thrips (en, ex)	1996
**Hypoaspis miles* (en)	Sciaridae, *Rhizoglyphus echinopus* (en)	1994
**Kampimodromus aberrans* (en)	Mites (*Panonychus ulmi)* (en)	1960
**Leptomastidea abnormis* (en)	Pseudococcidae (en, ex)	1984
**Leptomastix dactylopii* (ex)	*Planococcus citri* (en, ex)	1984
**Leptomastix epona* (en)	Pseudococcidae (en, ex)	1992
**Lysiphlebus fabarum* (en)	*Aphis gossypii* (ex)	1990
**Lysiphlebus testaceipes* (ex)	*Aphis gossypii* (ex)	1990
Macrolophus caliginosus (en)	Whiteflies (ex)	1994
**Macrolophus pygmaeus (nubilis)* (en)	Whiteflies (ex)	1994
**Metaphycus bartletti* (ex)	Coccidae (en, ex)	1997
**Metaphycus helvolus* (ex)	Coccidae (en, ex)	1984
**Metaseiulus occidentalis* (ex)	Mites (en)	1993
**Microterys flavus (ex)*	Coccidae (en, ex)	1987
**Microterys nietneri* (en)	Coccidae (en, ex)	1987
**Muscidifurax zaraptor* (ex)	Stable flies (en)	1982
**Nasonia vitripennis* (en)	Stable flies (en)	1982
**Neoseiulus barkeri* (en)	Mites (en), thrips (en, ex)	1990
Neoseiulus (Amblyseius) californicus (ex)	Mites (en, ex)	1995

Neoseiulus (Amblyseiu)s cucumeris (en, ex)	*Thrips tabaci* (en)	1985
	Frankliniella occidentalis (ex)	1986
	Mites (en, ex)	1990
Neoseiulus (Amblyseius) cucumeris (ex, non-diapause strain)	Thrips (en, ex)	1993
**Nephus reunioni* (ex)	Pseudococcidae (en,ex)	1990
**Ooencyrtus kuwanae* (ex)	Moth (*Lymantria dispar*) (en)	1980
**Ooencyrtus pityocampae* (ex)	*Thaumetopoea pityocampa* (ex)	1997
**Ophyra aenescens* (ex)	Stable flies (en 2 spp)	1995
Opius pallipes (en)	*Liriomyza bryoniae* (en)	1980
Orius spp. (en, ex)	*F. occidentalis/ T. tabaci* (ex, en)	
**Orius albidipennis* (en)		1991
Orius insidiosus (ex)		1991
Orius laevigatus (en)		1995
**Orius majusculus* (en)		1991
**Orius minutus* (en)		1991
**Orius tristicolor* (ex)		1995
**Paecilomyces fumosoroseus* (en)	Whiteflies (ex)	1997
**Phasmarhabditis hermaphrodita* (en)	Snails (en)	1994
**Phytoseiulus longipes* (ex)	*Tetranychus urticae* (en)	1990
Phytoseiulus persimilis (ex)	*Tetranychus urticae* (en)	1968
**Picromerus bidens* (en)	Lepidoptera (en)	1990
**Podisus maculiventris* (ex)	Lepidoptera (en, ex)	1996
	Leptinotarsa decemlineata (ex)	1996
**Praon volucre* (en)	Aphids (en)	1990
**Pseudaphycus angelicus* (ex)	Pseudococcidae (en, ex)	1990
**Pseudaphycus flavidulus* (en)	Pseudococcidae (en, ex)	1990
**Pseudaphycus maculipennis* (en)	*Pseudococcus* spp. (en)	1980
**Rhyzobius chrysomeloides* (ex)	*Matsococcus feytaudi* (ex)	1997
**Rhyzobius (Lindorus) lophanthae* (ex)	Diaspididae (en,ex), Pseudalacapsis pentagona	1980
**Rodolia cardinalis* (ex)	*Icerya purchasi* (ex)	1990
**Rumina decollata* (en)	Snails (en)	1990
**Scolothrips sexmaculatus* (en)	Mites, thrips (en, ex)	1990
**Scutellista caerulea (cyanea)* (ex)	Coccidae (en, ex)	1990
**Scymnus rubromaculatus* (en)	Aphids (en)	1990
**Spodoptera* NPV-virus (en)	*Spodoptera exigua* (ex)	1994
**Steinernema carpocapsae* (en)	*Otiorrhynchus sulcatus* and other spp. (en)	1984
Steinernema feltiae (en)	Sciaridae and other spp. (en)	1984
**Stethorus punctillum* (en)	Mites (en)	1995
**Stratiolaelaps miles* (en)	Sciaridae, *Rhizoglyphus echinopus* (en)	1994
**Sympherobius* sp. (en)	Pseudococcidae (en, ex)	1990
**Therodiplosis (=Feltiella) persicae* (en)	Mites in open fields (en)	1990
**Thripobius semiluteus* (ex)	Thrips (ex)	1995
**Trichogramma brassicae* (en)	Lepidoptera, several spp. (en)	1980
**Trichogramma cacoeciae* (en)	Lepidoptera, orchards, several spp (en)	1980
**Trichogramma dendrolimi* (en)	Lepidoptera, orchards, several spp (en)	1985
Trichogramma evanescens (en)	*Ostrinia nubilalis* in maize (en)	1975
Trichogramma evanescens (en)	Lepidoptera in greenhouses (en, ex)	1992
**Typhlodromus pyri* (en)	Mites in apple, pear, grapes	1985
**Verticillium lecanii* (en)	Whitefly/aphids (ex, en)	1990

** small market products*
endemic: occurs in European Union Countries
exotic: originates from outside European Union Countries, but may be in Europe for 50 years or more

10. Benefits and costs of biological control

Currently, this chapter contains a number of haphazardly collected examples and references about benefits and costs of biological control. In the course of rewriting of this book, a more complete picture will develop on worldwide benefits and costs of biological control. Please send the editor any information you have about this topic, and it will be included in this chapter.

Insect biological control

An overview of benefit and cost figures for a number of biological control projects can be found in Huffaker & Messenger (1976).

In Kenya, a landmark programme took place against a mealybug which began to devastate coffee plantations and food crops in the Kenya highlands in 1923. The mealybug was a new species, described as *Planococcus kenyae* Le Pelley. importations from Uganda, made in 1938, included two species of *Anagyrus* (Hymenoptera: Encyrtidae) which readily bred on *P. kenyae* and rapidly established following releases in the same year. By 1949 control was good in almost all areas and incipient outbreaks were controlled by the release of parasitoids. In 1959 it was estimated that some £10 million had been saved against an outlay of a total expenditure of not more that £30,000 (Greathead, 1971).

Huffaker, C.B. & P.S. Messenger eds. 1976. Theory and Practice of Biological Control. Academic Press, New York: 788 pp.

Weed biological control (see also special section on weed biological control

The track-record of weed biological control shows that as per the year 2000, 41 weed species have been successfully controlled somewhere in the world using introduced insects and pathogens (McFadyen, 2000). With many of these weeds, the successful control has been repeated in several countries and regions of the world and the savings to agriculture and the environment are enormous. Benefit cost ratios are in the order of 2.3 to 110:1; and these ratios increasing each year as chemical control is no longer needed. An overview of benefits and costs, as well as an overview of recent successes is provided by McFadyen (2003). Weed species brought under complete control are from very different groups and represent annual agricultural and environmental weeds, water weeds, perennial shrubs and trees. Financial and social benefits from control of water hyacinth and salvinia in particular have been enormous. Because waterways are used for transport and fisheries, irrigation and water supply, an entire society can be disrupted or even destroyed if dense mats of floating water weeds prevent movement between settlements. When salvinia was brought under biological control in Sri Lanka, the benefit cost ratio was calculated to be 1675:1; costs were so low because the natural enemy had already been tested and used elsewhere.

References

McFadyen, R.E.C., 2000. Sucesses in biological control. In N.R. Spencer (ed.), Proc. Xth Int. Symp. Biol. Control Weeds, Montana State University, Bozeman, MT, pp. 3-14.

McFadyen, R.E.C., 2003. Biological control of weeds using exotic insects. In: Predators and Parasitoids (O. Koul & G.S. Dhaliwal, eds.). Taylor & Francis, London, pp. 163-183.

11. Commercial and non-commercial producers of natural enemies

Under construction. This chapter is based on information from van Lenteren, J.C., 2003. Commercial availability of biological control agents. Chapter 11 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 167-179.

Although biological control of pests has been applied since around 1870, large-scale commercial use of natural enemies of pests spans a period of less than 40 years. In some areas of agriculture, such as apple orchards, corn, cotton, sugar cane, soybean, vineyards and greenhouses, it has been a very successful environmentally and economically sound alternative for chemical pest control (van Lenteren *et al.*, 1992; van Lenteren, 2000). Inundative and seasonal inoculative releases of natural enemies are commercially applied primarily in annual field crops and greenhouse cultures and have increased considerably over the last 25 years (van Lenteren, 2000). Success of biological control in these crops is primarily dependent on the quality of the natural enemies, which are produced by commercial mass-rearing companies.

Today, more than 150 natural enemy species are on the market for biological pest control (some 125 species are listed in a table in the chapter on Mass production, shipment and release of natural enemies). Worldwide, there are about 85 commercial producers of natural enemies for augmentative forms of biological control with a turnover of about 50 million US$ in 2000, and an annual growth of 15-20% (Bolckmans, 1999; K. Bolckmans, Berkel and Rodenrijs, The Netherlands, 2003, personal communication). In addition there are hundreds of state or farmer funded production units that may sell natural enemies (van Lenteren, 2000; van Lenteren & Bueno, 2003).

Commercial availability of natural enemies is changing continuously, although several of the larger producers are on the market for a period of 30 years now, which guarantees permanent presence of the most important agents. Updated versions of commercially available biological control organisms, companies and suppliers are published on a regular basis in the IPM Practitioner (Anonymous, 2005) and on the web (e.g. www.koppert.nl, www.biobest.be etc.). Less than thirty beneficial species make up 90% of the total sales (Bolckmans, 1999; van Lenteren, 1997). Extensive reviews of availability of commercially produced biological control agents had not been compiled until the mid 1990s, although some data are given in van Lenteren and Woets (1988). Cranshaw *et al.* (1996) correctly state that such information is essential for making calculations on the cost effectiveness of using such biological control organisms. Cranshaw *et al.* (1996) reviewed the 1994 pricing and marketing by suppliers of organisms for biological control of arthropods in the USA. The same was done for Europe (van Lenteren *et al.*, 1997). The most commonly sold species, including prices, are discussed in van Lenteren (2003). Most natural enemies in Europe are used for biological control in greenhouses, with the exception of *Harmonia* sp. and *Trichogramma* spp., which are also used in the open field.

The relative importance of the different natural enemies can be expressed also by their monetary value. Reliable data are available for biological control agents used in greenhouses (Bolckmans, 1999), but are lacking for field applications, although it is estimated that – expressed in monetary value - 80% of the commercially natural enemies are used in greenhouses. The vast amount of natural enemies used on about 16 million hectares of field crops mainly consist of non-commercial products that are reared in state funded laboratories. For these biological control agents cost estimates are often lacking. The most applied natural enemies in greenhouses are *E. formosa* accounting for 25% of the total market, *P. persimilis* accounting for 12% and *A. cucumeris* also accounting for 12%. Another good indicator of the significance of groups of natural enemies is the investment in money for control of the various groups of pests:

four groups of pests – whiteflies, thrips, spider mites and aphids – account for 84% of the costs of biological pest control.

Large differences in prices for biological control agents exist among the commercial companies (for details see van Lenteren *et al.*, 1997). A general observation is that there are many more species of natural enemies commercially available in Europe than in the USA, as a result of the much larger greenhouse industry in Europe. In comparison with the USA, it can also be concluded that commercial biological control suppliers in Europe are of larger size than their partners in the USA.

References

Anonymous (20005) Directory of least-toxic pest control products. *The IPM Practitioner*

Bolckmans, K.J.F, (1999) Commercial aspects of biological pest control. In: Albajes, R., Gullino, M.L., van Lenteren, J.C. and Elad, Y. (eds.) *Integrated Pest and Disease Management in Greenhouse Crops*, Kluwer Academic Publishers, Dordrecht, pp. 310-338

Cranshaw, W., Sclar, D.C. and Cooper, D. (1996) A review of 1994 pricing and marketing by suppliers of organisms for biological control of arthropods in the United States. *Biological Control* 6, 291-296.

Lenteren, J.C. van, (1997) Benefits and risks of introducing exotic macro-biological control agents into Europe. *Bulletin OEPP/EPPO* 27, 15-27.

Lenteren, J.C. van, (2000) Measures of Success in Biological Control Of Arthropods By Augmentation Of Natural Enemies. In: Measures of Success in Biological Control, G. Gurr & S. Wratten (eds.). Kluwer Academic Publishers, Dordrecht: 77-103.

Lenteren, J.C. van, (2003) Commercial availability of biological control agents. Chapter 11 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 167-179.

Lenteren, J.C. van & V.H.P. Bueno, (2003) Augmentative biological control of arthropods in Latin America. BioControl 48: 123-139.

van Lenteren, J.C., and Woets, J. (1988) Biological and integrated pest control in greenhouses. *Annual Review of Entomololgy* 33, 239-269.

van Lenteren, J.C., Roskam, M.M. and Timmer, R. (1997) Commercial mass production and pricing of organisms for biological control of pests in Europe. *Biological Control* 10, 143-149.

van Lenteren, J.C., Benuzzi, M., Nicoli, G., and Maini, S. (1992) Biological control in protected crops in Europe. In: van Lenteren, J.C., Minks, A.K. and de Ponti, O.M.B. (eds.) *Biological Control and Integrated Crop Protection*: *towards environmentally safer agriculture*. Pudoc, Wageningen, pp. 77-84.

Table 1. Most commonly used commercial biological control agents in Europe and North America (situation in the year 2000; after van Lenteren, 2003)

Amblyseius (Neoseiulus) californicus	*Delphastus pusillus*	*Macrolophus caliginosus*
Amblyseius (Neoseiulus) cucumeris	*Diglyphus isea*	*Metaphycus helvolus*
Amblyseius (Neoseiulus) degenerans	*Encarsia formosa*	Mesoseiulus longipes
Aphelinus abdominalis	*Eretmocerus californicus*	Orius insidiosus
Aphidius colemani	*Eretmocerus mundus*	*Orius laevigatus*
Aphidius ervi	*Galendromus occidentalis*	*Orius majusculus*
Aphidoletes aphidimyza	*Harmonia axyridis*	*Phytoseiulus persimilis*
Aphytis melinus	*Heterohabditis megides*	*Steinernema carpocapsae*
Chrysoperla carnea & rufilibris	*Hippodamia convergens*	*Steinernema feltiae*
Cryptoleamus montrouzieri	*Hypoaspis aculeifer*	*Trichogramma brassicae*
Dacnusa sibirica	*Hypoaspis miles*	*Trichogramma evanescens*
	Leptomastix abnormis	*Trichogramma spp.*
	Leptomastix dactylopii	Fly parasitoids, various species
	Leptomastix epona	

Table 2. Number of mass production facilities per country/region (under construction; van Lenteren, unpublished, situation 2004)

Country	Mass producers*	
	Commercial	Non-commercial
Argentina	1 (small)	
Australia	3 (small** – medium)	
Austria	2 (small)	
Belgium	1 (large; > 50)	
Brazil	5 (small – medium)	44
Canada	4 (small)	
Chile	6 (small)	2
China		many
Czech Republic	1 (small)	
Colombia	?	14
Cuba		220
Denmark	1 (small)	
France	3 (small – medium)	
Germany	10 (small – medium)	
Hungary	1 (small)	
Israel	2 (small – medium)	
Italy	2 (small – medium)	
Mexico	?	30
New Zealand	1 (small)	
Peru		109
Russia	?	several
South Korea	1 (small)	
Switzerland	2 (small – medium)	
Uruguay	1 (small – only pathogens)	1 (small, parasitoids)
The Netherlands	5 (small – medium – large)	
UK	5 (small – medium)	
USA	10 (small – medium)	

*website addresses of mass producers can be found in chapter 11
**small = < 10 persons employed, medium = 10-50 persons, large = > 50 persons

Release of natural enemies in Arizona, USA

12. Quality control of natural enemies

The material of this chapter is based largely on Lenteren, J.C. van (ed.), 2003. Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. CABI Publishing, Wallingford, UK: 327 pp.

Introduction

Augmentative biological control, where large numbers of natural enemies are periodically introduced, is commercially applied on a large area in various cropping systems worldwide, is a popular control method applied by professional and progressive farmers, and stimulated by the present international attitudes in policies of reducing pesticide use (van Lenteren, 2000a; van Lenteren & Bueno, 2003). Initially augmentative biological control was used to manage pests that had become resistant to pesticides. Now it is applied because of efficacy and costs, which are comparable with conventional chemical control. Farmers are also motivated to use biological control to reduce environmental effects caused by pesticide usage.

Worldwide more than 150 species of natural enemies are commercially available for augmentative biological control (Anonymous, 2005; Gurr and Wratten, 2000, van Lenteren 2003c). This form of control is applied in the open field in crops that are attacked by only a few pest species, and it is particularly popular in greenhouse crops, where the whole spectrum of pests can be managed by different natural enemies (van Lenteren, 2000b). Its popularity can be explained by a number of important benefits when compared with chemical (see introduction for advantages of biological control).

For a long time, natural enemies were produced without proper quality control procedures. Poorly performing natural enemies resulted in a failures of biological control and a low profile of this pest control methods (e.g. P. DeBach, Riverside, California, 1976 and P. Koppert, Berkel and Rodenrijs, The Netherlands, 1980, personal communications). Quality control was touched upon by several biological control workers in 20th century, but the first papers seriously addressing the problem appeared only in the 1980s (van Lenteren, 1986a).

The literature on quality control of mass produced arthropods presents several examples of poorly functioning organisms when quality control guidelines are not applied or neglected (e.g. Calkins and Ashley, 1989). Cases where inferior natural enemies resulted in failure of biological control are well known among the biocontrol community, but are seldomly published. The following text, concerning a failure in biocontrol and the way how this was solved by applying quality control, comes from Bigler (1994): "In Switzerland, *Trichogramma brassicae* has been mass-produced since 1975 and applied commercially against the European corn borer, *Ostrinia nubilalis*, in maize since 1978. A significant loss in field efficacy was observed in 1980 (Figure 19.1). By changing the mass-production system and the colony maintenance, it was possible to improve the performance of the strain and achieve the efficiency limit of at least 75% parasitisation in the field. A thorough analysis of the production system and the performance requirements of *T. brassicae* under the maize growing conditions in Switzerland led to the discovery of important traits which are crucial for a high efficacy. Since attributes like locomotory activity, host acceptance, host suitability and temperature tolerance were negatively affected by the former rearing system, a new production unit was developed. At the same time, risk evaluations of other deteriorations in the strain were performed and methods for measuring single traits and the field performance were developed. Bigler (1994) concludes that "Quality control in *Trichogramma* mass-rearings is one of the measures used to avoid failures in biological control with these parasitoids. The extremely artificial rearing conditions, compared to the habitat where they are released, call for the establishment of sophisticated quality control concepts. [….]. The importance of single performance attributes has to be established and related to field performance. The methods must be quick, simple and reliable. A single trait will never predict the overall performance accurately and therefore, the best combination of a set of laboratory methods must be developed. Whereas performance of the parasitoids in the field is the best indication of a good rearing system, low field efficacy does not tell us the causes. Regular performance control, carried out in the laboratory, will either indicate deterioration of performance and initiate corrections, or make us confident to produce wasps that are within the quality specifications."

Initial developments in the area of mass production, quality control, storage, shipment and release of natural enemies have decreased production costs and led to better product quality, but much more can be done. Innovations in long-term storage (e.g., through induction of diapause), shipment and release methods, may lead to a further increase in natural enemy quality with a concurrent reduction in costs, thereby making biological control easier and economically more attractive to apply. Even if the natural enemies leave the insectary in good condition, shipment and handling by the producers, distributors and growers may result in deterioration of the biological control agents before they are released.

The objectives of quality control

Quality control programmes are applied to mass-reared organisms to maintain the quality of the population. The overall quality of an organism can be defined as the ability to function as intended after release into the field. The aim of quality control programmes is to check whether the overall quality of a species is maintained, but that is too general a statement to be manageable. Characteristics that affect overall quality have to be identified. These characteristics must be quantifiable and relevant for the field performance of the parasitoid or predator. This is a straightforward statement, but very difficult to actually carry out (Bigler, 1989).

Rather than discussing the development of quality control in strictly scientific terms, this discussion will outline a more pragmatic approach. The aim of releases of mass-produced natural enemies is to control a pest. In this context the aim of quality control should be to determine whether a natural enemy is still in a condition to properly control the pest. Formulated in this way we do not need to consider terms like maximal or optimal quality, but rather acceptable quality. Some researchers believe the aim of quality control should be to keep the quality of the mass-reared population identical to that of the original field population. This is not only an illusion, it is an unnecessary and expensive goal to pursue. Another important consideration is that quality control programmes are not applied for the sake of the scientist, but as a mere necessity. Leppla and Fisher (1989) formulated this dilemma as "Information is expensive, so it is important to separate "**need** to know from **nice** to know." Only if characteristics to be measured are very limited in number, but directly linked to field performance, will companies producing natural enemies ever be able to apply quality control programmes on a regular basis.

Before starting a quality control programme, one should realize there are many basic considerations and obstacles to be overcome; careful evaluation of these obstacles and considerations is essential (van Lenteren, 2003b).

IOBC initiative on quality control

Although augmentative types of biological control of arthropod pests have been applied since 1926, large-scale production of natural enemies began only after the Second World War (DeBach, 1964). Initial mass rearing efforts involved the production of not more than several thousand individuals per week of three natural enemies: the spider mite predator *P. persimilis,* the whitefly parasitoid *E. formosa* and the lepidopteran egg parasitoid *Trichogramma* sp..

None of the early publications on commercial aspects of biological control mention the topic of quality control of natural enemies. Quality control is but mentioned in relation to biological control in the mid 1980s, and shortly after that the topic gained more interest (van Lenteren, 1986a, b). The 5th workshop of the International Organization for Biological Control (IOBC) global working group "Quality Control of Mass Reared Arthropods" (Bigler, 1991) in Wageningen, the Netherlands, formed the starting point for a heated discussion among producers of natural enemies and scientists on how to approach quality control in the commercial setting at that time.

A series of IOBC workshops, some partly, others largely funded by the EC, followed in Europe (1992, 1993, 1994, 1996, 1997; van Lenteren (2000b)). As a result of these meetings, quality control guidelines were written for more than 20 species of natural enemies, and these have been tested and adapted by commercial producers of biological control agents in Europe (van Lenteren and Tommasini, 1999). The guidelines cover features that are relatively easy to determine in the laboratory (e.g., emergence, sex ratio, lifespan, fecundity, adult size, predation/parasitism rate). Work is now focused on development of (1) flight tests and (2) a test relating these laboratory characteristics to field efficiency.

Recently, the International Biocontrol Manufacturers Association (IBMA) has taken the initiative to update and further develop quality control guidelines and fact sheets. Their first meeting, with participation of the most important European mass producers of natural enemies and represented by mass producers from Canada and the USA under the umbrella of the Association of Natural Bio-control Producers (ANBP) took place in September 2000 in the Netherlands and was followed up by a meeting in North America in 2001. The quality control guidelines for more than 30 species of natural enemies developed so far, are presented in van Lenteren et al. (2003) and on the IOBC-Global website (www.IOBC-Global.org under Working Group Arthropod Mass Production and Quality Control (AMRQC), or directly at www.AMRQC.org).

State of affairs concerning application of quality control world wide

Currently, quality control guidelines as presented by van Lenteren et al. (2003) are applied by several companies that mass produce natural enemies in Europe and North America. Depending on the size of the company and the number of natural enemy species that they produce, they may apply from 1 to more than 20 tests. Through correspondence and literature search the following information was obtained for other countries.

In the former Soviet Union quite some work was done during the 1980's on quality control of *Trichogramma*, a parasitoid that was used on several million hectares for control of a various lepidopteran pests. References to this work, as well as examples of USSR quality control programmes can be found in one Russian paper in the Proceedings of the 1st International Symposium on *Trichogramma* and other egg parasitoids (Voegele, 1982), in three papers authored by Russian researchers the Proceedings of the 2nd International Symposium on *Trichogramma* and other egg parasites (Voegele *et al.*, 1988), and several papers published in later proceedings of this working group (2 papers in Wajnberg and Vinson, 1991, 3rd symposium; 5 papers in Wajnberg, 1995, 4th symposium). Most of the elements of quality control discussed in these papers are included in the current quality control guidelines (van Lenteren et al., 2003).

Information on quality control of mass produced natural enemies used in China is not easy to trace, although inundative and seasonal inoculative forms of biological control are use on about 1 million hectares. Aspects of quality control are described in two Chinese papers in the Proceedings of the 1st International Symposium on *Trichogramma* and other egg parasitoids (Voegele, 1982), in about 10 papers authored by Chinese researchers in the Proceedings of the 2nd International Symposium on *Trichogramma* and other egg parasites

(Voegele *et al.*, 1988), in 5 papers by Chinese in Wajnberg and Vinson, 1991 (3rd symposium), and in 4 papers by Chinese in Wajnberg, 1995 (4th symposium). Details are not described here, because very few papers specifically address quality control, and most of the useful components of the Chinese quality control studies are included in the present guidelines for *Trichogramma* and other egg parasitoids (van Lenteren et al., 2003). An exception is a simple quality control method that I saw demonstrated in one of the *Trichogramma* mass production units in the Biocontrol Station of Shun-de County, near the town of Ghuanzhou, Province of Guangdong, China. Parasitoids were reared on silk worm eggs, adult parasitoids were allowed to emerge at the dark side of the room, fresh host eggs were offered at the light side of the room near a window about 3 meters away from the dark side, so the freshly emerged parasitoids had to fly several meters before they could parasitise hosts. In this way non-flying parasitoids were prevented from reproduction (van Lenteren, Ghuandong, China, November 1986, personal observation).

Australian producers are applying one full quality control guideline – the one for *Aphytis* as specified in van Lenteren et al. (2003) – and are using elements of the other IOBC guidelines. There are no Australian publications on quality control. A set of guidelines for natural enemies that are specifically applied in Australia is in development. Genetic diversity and rejuvenation of laboratory material with field collected natural enemies forms a specific point of interest of Australian producers (all information from D. Papacek, Australia, April 2001, personal communication). In New Zealand, elements of the IOBC guidelines are used for quality control of about 5 species of natural enemies, and critical point standards for quality checks during the production process are in development; there are no publications from New Zealand on quality control (R. Rountree, New Zealand, April 2001, personal communication). In Japan, elements of the IOBC guidelines are used for quality control of several species of natural enemies that are imported from Europe or produced in Japan; there are no Japanese publications on quality control (E. Yano, Japan, April 2001, personal communication). Elements of quality control are applied in India to evaluate the quality of mass reared *Trichogramma* (Kaushik and Arora, 1998; Swamiappan *et al.*, 1998).

The Insectary Society of Southern Africa is actively developing a set of minimum quality control standards for insects commercially for sale as biocontrol agents and other purposes, developments are discussed bi-annual Insect Rearing Workshops, and progress is reported in the proceedings of these workshops (see e.g. Conlong, 1995) (D. Conlong, South Africa, April 2001, personal communication,). In several other African countries like Benin, Kenya, Nigeria, Sudan, Zambia, quality control is applied (Conlong, 1995; Conlong and Mugoya, 1996; van Lenteren, Africa, 1983-2001, personal observations), but it is not easy to trace published material providing detail about the methodology, with the exception of work done at IITA (e.g. Yaninek and Herren, 1989).

The situation concerning quality control in Latin America is even less clear than in other areas of the world. Recently two rather detailed papers appeared on quality control of a tachinid parasitoid (Aleman *et al.*, 1998) and predatory mites (Ramos *et al.*, 1998) as performed in Cuba. Also, a book edited by Bueno (2000) provides examples of quality control for microbials, predatory mites, and predatory and parasitic insects in Brazil, but few details about methodology are provided. Based on the vast areas under augmentative biological control in Latin America (van Lenteren and Bueno, 2003), I suppose that there is much more done on quality control than could be traced in the literature.

Development and implementation of quality control

Natural enemies are often mass produced under conditions that are very different to those found in commercial crops. Also, the development of quality control programmes for natural enemy production has been rather pragmatic. The guidelines described in this chapter refer to product control procedures, not to production or process control. They were designed to be as uniform as possible so they can be used in a standardised manner by many producers, and elements of the tests can be used by distributors, pest management advisory personnel and farmers. The standard elements of the quality control guidelines are given in table 1. The tests should preferably be carried out by the producer after all handling procedures just before shipment. It is expected that the user (farmer) only performs a few aspects of the quality test, e.g., percent emergence or number of live adults in the package. Some tests are to be carried out frequently by the producer, i.e., on a daily, weekly or batch-wise basis. Others will be done less frequently, i.e., on an annual or seasonal basis, or when rearing procedures are changed. In the near future, flight tests and field performance tests are expected to be added to these guidelines. Such tests are needed to show the relevance of the laboratory measurements. Laboratory tests are only adequate when a good correlation has been established between the laboratory measurements, flight tests and field performance.

Table 1. General quality control criteria for mass reared natural enemies (after van Lenteren et al., 2003)

Criteria alrealy in use:

Quantity: number of live natural enemy organisms in container
Sex ratio: minimum percentage females (male biased ratio may indicate poor rearing conditions)
Emergence: emergence rate to be specified for all organisms sold as eggs or pupae
Fecundity: number of offspring produced during a certain period (for parasitoids fecundity is also an indication of the host kill rate)
Longevity: minimum longevity in days
Parasitism: number of hosts parasitized during a certain period
Predation: number of prey eaten during a certain period
Adult size: hind tibia length of adults, sometimes pupal size (size is often a good indication for longevity, fecundity and parasitization/predation capacity)

Criteria to be added in near future:

Flight: short- or long-range flight capacity
Field performance: capacity to locate and consume prey or parasitize hosts in crop under field conditions

Comments:

- Quality control is done under standardised test conditions of temperature (usually 22 ± 2^o C or 25 ± 2^o C), relative humidity (usually 75 ± 10 %) and light regime (usually 16 L : 8 D), that are specified for each test
- All numbers / ratios / sizes should be mentioned on the container or packaging material
- Fecundity, longevity and predation capacity tests can often be combined
- Expiration date for each shipment should be given on packaging material
- Guidelines should be usable for all product formulations

Original designers: names of the persons who made the first design of the guideline
Coordinators: names of the persons who collect new information for the guideline and will adapt the guideline when needed;
Updateted guidelines: will be available at www.AMRQC.org (via www.IOBC-Global.org, go to working group AMRQC = Arthropod Mass Rearing and Quality Control)

The quality control guidelines presented in this chapter are applied by a number of companies that mass produce natural enemies in Europe and North America, and are used by others to compare performance of the same species of natural enemy produced by different companies (e.g. Hassan and Wen, 2001; O'Neil *et al.,* 1998)). Depending on the size of the company and the number of natural enemy species that they produce, they may apply from 1 to more than 20 tests. The natural enemy species for which tests are available are listed in table 2. Understandingly, very few data are made public by the companies, although extensive exchange of information of test results took place during the development of the quality control guidelines from 1991-1998. Nowadays, the biocontrol industry has developed a ring testing system for development guidelines for new species of natural enemies and adaptation of old guidelines.

Table 2. Natural enemies for which quality control guidelines have been developed (after van Lenteren et al., 2003)

Amblyseius (Neoseiulus) degenerans Berlese (Acarina: Phytoseiidae)	
Anthocoris nemoralis (Fabricius) (Hemiptera: Anthocoridae)	Provisional test
Aphelinus abdominalis Dalman (Hymenoptera: Aphelinidae)	Provisional test
Aphidius colemani Viereck (Hymenoptera: Braconidae)	
Aphidius ervi (Haliday) (Hymenoptera: Braconidae)	
Aphidoletes aphidimyza (Rondani) (Diptera: Cecidomyiidae)	
Aphytis lingnanensis Compere & *A. melinus* DeBach (Hymenoptera: Aphelinidae)	
Chrysoperla carnea Steph. (Neuroptera: Chrysopidae)	Provisional test
Cryptolaemus montrouzieri Mulsant (Coleoptera: Coccinellidae)	Provisional test
Dacnusa sibirica Telenga (Hymenoptera: Braconidae)	
Dicyphus hesperus Wagner (Hemiptera: Miridae)	
Diglyphus isaea (Walker) (Hymenoptera: Eulophidae)	
Encarsia formosa Gahan (Hymenoptera: Aphelinidae)	
Eretmocerus eremicus (Rose) (Hymenoptera: Aphelinidae)	
Eretmocerus mundus Mercet (Hymenoptera: Aphelinidae)	Provisional test
Hypoaspis miles Berlese (Acari: Laelapidae)	Provisional test
Leptomastix dactylopii Howard (Hymenoptera: Encyrtidae)	
Macrolophus caliginosus Wagner (Hemiptera: Miridae)	
Neoseiulus californicus McGregor (Acarina: Phytoseiidae)	
Neoseiulus cucumeris (Oudemans) (Acarina: Phytoseiidae)	
Orius spp. (*O.laevigatus, O. insidiosus, O. majusculus, O. aldibipennis*) (Hemiptera: Anthocoridae)	
Phytoseiulus persimilis Athias-Henriot (Acarina: Phytoseidae)	
Podisus maculiventris Say (Hemiptera: Pentatomidae)	Provisional test
Trichogramma brassicae Bezd. (=*T. maidis*) (Hymenoptera: Trichogrammatidae)	
Trichogramma cacoeciae Marchal (Hymenoptera: Trichogrammatidae)	
Trichogramma dendrolimi Matsumura (Hymenoptera: Trichogrammatidae)	

Future additions to current quality control guidelines

The producers of natural enemies work together with biological control researchers to develop flight tests and field performance tests. The importance of these flight tests has been discussed by several authors (see e.g. Bigler (1994), but testing of these aspects is still rare. Flight tests are supposed to be essential to determine quality if the natural enemy has been reared under conditions where flight was not needed to find hosts or prey, which is often the case under crowded mass rearing conditions. Flight tests are also needed when the natural enemy is seriously manipulated during mass rearing and preparation for shipment (e.g. removal of pupae from leaves and gluing pupae to cardboard cards), and when storage periods are long (see chapter on mass production). Correlation between values obtained at laboratory testing and field performance is important to be able to select a limited set of laboratory criteria that give meaningful information about performance after release.

Bigler (1994) provides information about laboratory testing and field performance. Also Silva *et al.* (2000) describe and use an interesting test that was initially developed by Greenberg (1991) to evaluate searching and dispersal ability of parasitoids in a maze in the laboratory. Silva et al. (2000) measured the performance of *Trichogramma* in a maze in the laboratory to predict its dispersal capacity in the field. An interesting approach for a field performance test has been described by van Schelt and Ravensberg (1990). Their goal was to compare the capacity to control *O. nubilalis* in corn by *T. maidis* that were either obtained from diapause storage or freshly reared. In the laboraratory, percentage emergence, sex ratio and fecundity were determined of diapause and freshly reared parasitoids. Vials with parasitoids of the same samples as the laboratory material were put at a central release point in a corn crop. From the release point, cards with sentinel *O. nubilalis* eggs were hung on corn plants in 8 directions, with an interval of 1 meter and up to 10 meters away from the release point. Percentage parasitism was determined on these cards. The laboratory results showed no differences in emergence and fecundity between the diapause and fresh parasitoids, but the sex ratio of the diapause parasitoids was lower than that of fresh ones. The field tests showed that diapause and fresh parasitoids dispersed in all directions, but that percentage parasitism by fresh parasitoids was higher than that of diapause parasitoids (van Schelt and Ravensberg, 1990). The results obtained with one of the flight tests are described below to illustrate developments in this area.

A short-range flight test has been developed for *Encarsia formosa*, i.e. a test where the parasitoid has to fly a distance of 4 - 20 cm (van Lenteren et al., 2003). Such distances are similar to distances between leaves in a plant. We have experienced that some methods of producing or storing *E. formosa* can lead to defective individuals that are unable to fly even such short distances, and that was the reason for developing this test. This short-range flight test is run in a glass cylinder that has a glass cover with sticky material on the underside. A barrier of repellent material (e.g. Blistex lippomade), 4 cm in height, is applied to the vertical wall of the cylinder to prevents wasps from walking to the sticky material on the glass cover plate at the top (Figure 19.2). Parasitoids are put on leaves or on cards on the bottom of the cylinder. The whole set-up consists of standardised parts, is easy to assemble and reusable, and uses a small amount of space (400 cm^2) per glass cylinder. Counting of the trapped wasps can be done rapidly (2 minutes per cylinder) and without manipulation of the cylinder. The effects of parasitoid rearing, handling and storage conditions can be evaluated with this test. This test can be used also for concurrent measurement of immature mortality, and parasitoid emergence pattern, elements, which that are included in the current quality control guideline.

The short-range flight test is suitable, among others, for evaluating the effect of storage periods, temperature and handling procedures on the flight capability of *E. formosa* and is expected to be included in the standard testing procedure in the near future. This short-range flight test has already provided important additional information to the quality control measurements discussed above. A short-range flight test based on the one used for *E. formosa* has been developed for *Trichogramma* by Dutton and Bigler (1995) and is discussed by Prezotti and Parra (2002). Flight tests need further improvement for easy and reliable use.

In addition to the quality control tests, fact sheets for natural enemies and pests should be prepared to inform new quality control personnel and plant protection services on biological details.

References

Aleman, J., Plana L., Vidal, M., Llanes, G. and Delgado, M. (1998) Criterios para el control de la calidad en la cria masiva de *Lixophaga diatraeae*. In: Hassan, S.A. (ed.) *Proceedings of the 5th International Symposium on Trichogramma and other egg parasitoids*, 4-7 March 1998, Cali, Colombia, pp. 97-104.

Anonymous (2005) 2006 Directory of least-toxic pest control products. *The IPM Practitioner*.

Bigler, F. (1989) Quality assessment and control in entomophagous insects used for biological control. *Journal of Applied Entomology* 108, 390-400.

Bigler, F. (1991) Quality Control of Mass Reared Arthropods. *Proceedings 5th Workshop IOBC Global Working Group "Quality Control of Mass Reared Arthropods"*, 25-29 March 1991, Wageningen, The Netherlands, 205 pp.

Bigler, F. (1994) Quality control in *Trichogramma* production. In: Wajnberg, E. and Hassan, S.A. (eds) *Biological Control with Egg Parasitoids.* CABI International, Wallingford, Oxon, pp. 93-111.

Bueno, V.H.P. (2000) Controle biologico de pragas: producao massal e controle de qualidade. Editora UFLA, Lavras, Brazil (in Portuguese), 215 pp.

Calkins, C.O. and Ashley, T.R. (1989) The impact of poor quality of mass-reared Mediterranean fruit flies on the sterile insect technique used for eradication. *Journal of Applied Entomology* 108, 401-408.

Conlong, D.E. (1995) Small colony initiation, maintenance and quality control in insect rearing. *Proceedings 4th National Insect Rearing Workshop*, Grahamstown, South Africa, 3 July 1995, 39 pp.

Conlong, D.E. and Mugoya, C.F. (1996) Rearing beneficial insects for biological control purposes in resource poor areas of Africa. *Entomophaga* 41, 505-512.

DeBach, P., ed. 1964. Biological Control of Insect Pests and Weeds. Cambridge Univ. Press, Cambridge: 844 pp.

Dutton, A. and Bigler, F. (1995) Flight activity assessment of the egg parasitoid *Trichogramma brassicae* (Hym.: Trichogrammatidae) in laboratory and field conditions. *Entomophaga* 40, 223-233.

Greenberg, S.M. (1991) Evaluation techniques for *Trichogramma quality*. In: Bigler, F. (ed.) *Quality Control of Mass Reared Arthropods*. Proceedings 5th Workshop IOBC Global Working Group "Quality Control of Mass Reared Arthropods", 25-29 March 1991, Wageningen, The Netherlands, pp. 138-145.

Gurr, G. and Wratten, S. (eds.) (2000) *Measures of Success in Biological Control*. Kluwer Academic Publishers, Dordrecht, 448 pp.

Hassan, S.A. and Wen Qing Zhang (2001) Variability in quality of *Trichogramma brassicae* (Hymenoptera: Trichogrammatidae) from commercial suppliers in Germany. *Biological Control* 22, 115-121.

Kaushik, H.D. and Arora, R.K. (1998) *Trichogramma*: research and use in India. In: Hassan, S.A.(ed.) *Proceedings of the 5th International Symposium on Trichogramma and other egg parasitoids,* 4-7 March 1998, Cali, Colombia, pp. 155-176.

Lenteren, J.C. van (1986a) Evaluation, mass production, quality control and release of entomophagous insects. In: Franz, J.M (ed.) *Biological Plant and Health Protection.* Fischer, Stuttgart, Germany, pp. 31-56.

Lenteren, J.C. van (1986b) Parasitoids in the greenhouse: successes with seasonal inoculative release systems. In: Waage, J.K. and Greathead, D.J. (eds.) *Insect Parasitoids*. Academic Press, London, pp. 341-374.

Lenteren, J.C. van (2000a) Measures of success in biological control of arthropods by augmentation of natural enemies. In: Gurr, G. and Wratten, S. (eds.) *Measures of Success in Biological Control*. Kluwer Academic Publishers, Dordrecht, pp. 77-103.

Lenteren, J.C. van (2000b) A greenhouse without pesticides: fact of fantasy? *Crop Prote*ction 19, 375-384.

Lenteren, J.C. van, and Bueno, V.H.P. (2003) Augmentative biological control in Latin America as seen from a worldwide perspective. *BioControl*, submitted.

Lenteren, J.C. van (ed.), 2003a. Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. CABI Publishing, Wallingford, UK: 327 pp.

Lenteren, J.C. van, 2003b. Need of quality control of mass-produced biological control agents. Chapter 1 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 1-18.

Lenteren, J.C. van, 2003c. Commercial availability of biological control agents. Chapter 11 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 167-179.

Lenteren, J.C. van & V.H.P. Bueno, 2003. Augmentative biological control of arthropods in Latin America. BioControl 48: 123-139.

Lenteren, J.C. van, and Tommasini, M.G. (1999) Mass production, storage, shipment and quality control of natural enemies. In: Albajes, R., Gullino, M.L., van Lenteren, J.C. and Elad, Y. (eds.) *Integrated Pest and Disease Management in Greenhouse Crops.* Kluwer Academic Publishers, Dordecht, The Netherlands, pp. 276-294.

Lenteren, J.C. van & M.G. Tommasini, 2003. Mass Production, Storage, Shipment and Release of Natural Enemies. Chapter 12 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 181-189.

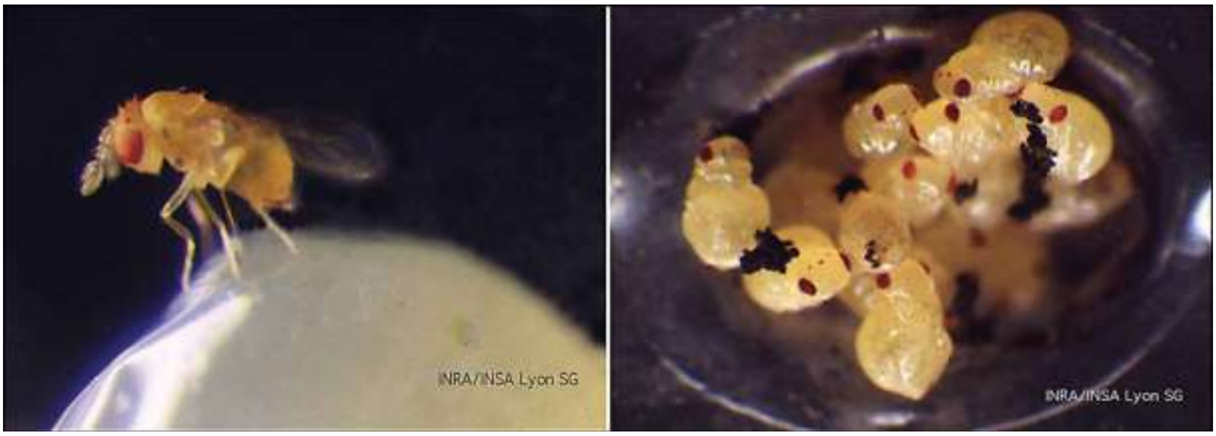
Lenteren,J.C. van, A. Hale, J.N. Klapwijk, J. van Schelt and S. Steinberg, 2003. Guidelines for quality control of commercially produced natural enemies. Chapter 19 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 265-303.

Leppla, N.C. and Fisher, W.R. (1989) Total quality control in insect mass production for insect pest management. *Journal of Applied Entomology* 108, 452-461.
O'Neil, R.J., Giles, K.L., Obrycki, J.J., Mahr, D.L., Legaspi, J.C., and Katovich, K. (1998) Evaluation of the quality of four commercially available natural enemies. *Biological Control* 11, 1-8.
Prezotti, L. and Parra, J.R.P. (2002) Controle de qualidade em criacoes massais de parasitoides e predadores. In: Parra, J.R.P, Botelho, P.S.M., Correa-Ferreira, B.S. and Bento, J.M.S. (eds.) *Controle Biologico no Brasil: Parasitoides e Predadores*. Manole, Sao Paulo, pp. 295-311.
Ramos, M., Aleman, J., Rodriguez, H. and Chico, R. (1998). Estimacion de parametros para el control de calidad en crias de *Phytoseiulus persimilis* (Banks) (Acari: Phytoseiidae) empleando como presa a *Panonychus citri* McGregor (Acari: Tetranychidae). In: Hassan, S.A. (ed). *Proceedings of the 5th International Symposium on Trichogramma and other egg parasitoids*, 4-7 March 1998, Cali, Colombia, pp. 109-118.
Schelt, J. van and Ravensberg, W.J. (1990) Some aspects on the storage and application of *Trichogramma maidis* in corn. In: Wajnberg, E. and Vinson, S.B. (eds.) *Proceedings of the 3rd International Symposium on Trichogramma and other egg parasitoids*, 23-27 September 1990, San Antonio, USA.. Les Colloques de l'INRA 56, Paris, pp. 239-242.
Silva, I.M.M.S., van Meer, M.M.M., Roskam, M.M., Hoogenboom, A., Gort, G. and Stouthamer, R. (2000) Biological control potential of *Wolbachia*-infected versus uninfected wasps: laboratory and greenhouse evaluation of *Trichogramma cordubensis* and *T. deion* strains. *Biocontrol Science and Technology* 10, 223-238.
Swamiappan, M., Muthuswami, M. and Sithanantham, S. (1998) Quality control of mass reared *Trichogramma* in commercial laboratories in Tamil Nadu, India. In: Hassan, S.A. (ed.) *Proceedings of the 5th International Symposium on Trichogramma and other egg parasitoids*, 4-7 March 1998, Cali, Colombia, pp.105-108.
Voegele, J. (ed.) (1982) *Proceedings of 1er Symposium International sur Les Trichogrammes*, 20-23 April 1982, Antibes, France. Les Colloques de l'INRA 9, Paris, 307 pp.
Voegele, J., Waage, J. and van Lenteren, J.C. (eds.) (1988) *Proceedings of the 2nd International Symposium on Trichogramma and other egg parasites*, 10-15 November 1986, Guangzhou, China. Les Colloques de l'INRA 43, Paris, 644 pp.
Wajnberg, E. (ed.) (1994) *Proceedings of the 4th International Symposium on Trichogramma and other egg parasitoids*, 4-7 October 1994, Cairo, Egypt. Les Colloques de l'INRA 73, Paris, 226 pp.
Wajnberg, E. and Vinson, S.B. (eds.) (1990) *Proceedings of the 3rd International Symposium on Trichogramma and other egg parasitoids*, 23-27 September 1990, San Antonio, USA.. Les Colloques de l'INRA 56, Paris, 246 pp.
Yaninek, J.S. and Herren, H.R. (1989) Biological control: a sustainable solution to crop pest problems in Africa. IITA, Ibadan, Nigeria, 194 pp.

Encarsia formosa, quality control

13. Artificial rearing of natural enemies and quality control

The text of this chapter is mainly based on: Grenier, S. and P. DeClerq, 2003. Comparison of Artificially vs. Naturally Reared Natural Enemies and Their Potential for Use in Biological Control, Chapter 12 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 181-189.



***Trichogramma* laying eggs in artificial host (left) and *Trichogramma* pupa that developed in artificial hosts (right) (Photographs S. Grenier, Lyon)**

Introduction

A step in making mass rearing of natural enemies more economical is to change from a natural host medium (host plant) to an artificial medium for rearing the host. Rearing insects on artificial diets was developed earlier this century and considerable progress has been made recently. Rearing on artificial diets is considerably cheaper as less expensively climatized space is needed, but artificial rearing may create serious quality problems. Singh (1984) summarized the historical development, advances and future prospects for insect diets. Currently, some 750 species, mainly phytophagous insects can be reared successfully on (semi-) artificial diets, but only about two dozen species have been successfully reared for several generations on completely artificial diets. Large scale mass rearing on artificial media has been developed for less than twenty species of insects. Quality control is essential, as there can be dietary effects on all critical performance traits of the mass-reared insect and also on the natural enemy produced on a host that was mass reared on an artificial medium, and suitable bioassays are important for answering the question "what is the ultimate effect of the diet on the reared insect?" A final step when trying to minimize rearing costs is the search for ways to rear the natural enemy on an artificial diet. This has been attained for several ecto- and endoparasitoids (e.g. *Trichogramma*) and a few predators (e.g. *Chrysoperla*). The technology for rearing natural enemies on diets is, however, far less developed than that for rearing of pest species (Grenier & DeClercq, 2003; De Clercq, 2004). In this chapter the kind of artificial diets, some examples of artificially reared arthropods and quality control aspects are discussed.

Different kinds of artificial diets for parasitoids and predators

Long ago some terms were used to characterize diets based on the presence or absence of complex components, but they were not so clearly defined: holidic media (chemical structure of all ingredients known), meridic media (holidic base to which at least one substance or preparation of unknown structure or uncertain purity is added), or oligidic media (crude organic materials). These distinctions are not very relevant, because only a complete description of the composition of a diet would be able to characterize it. Nevertheless for practical considerations, a critical characteristic is the presence or the absence of insect components. Thus, considering that synthetic diets were supposed to replace the insect host or prey, it is worthy to distinguish two main kinds of media: those including and those excluding insect components. Addition of insect materials implies the necessity to culture not only the host but often also the host's food plant, rendering entomophage production more expensive. But we have to emphasize that in some parts of the world, especially in China and some other Asian countries, and in Latin America, insect components such as hemolymph could be side-products from the silk industry, and thus cheap and easy to obtain.

Diets with insect additives

Insect additives can be used in different ways. Sometimes nearly the whole host contents are used as scarcely diluted extracts. The main elements used are whole body tissue extracts or hemolymph from lepidopterous pupae in artificial diets for parasitoids. This is the case for larval parasitoids, such as the chalcidid *Brachymeria intermedia* (Dindo *et al.*, 1997) and the ichneumonid *Diapetimorpha introita* (Ferkovich *et al.*, 1999; 2000), or the tachinid *Exorista larvarum* (Dindo *et al.*, 1999), and oophagous parasitoids, such as *Trichogramma* spp. (for a review see Grenier, 1994). Usually silkworm species (*Antheraea pernyi*, *Philosamia cynthia*) and easily reared insects like *Galleria mellonella* are used for these extracts. Bee extracts or even whole pulverized bees or bee brood have been added in diets for coccinellid predators (Smirnoff, 1958; Niijima *et al.*, 1977, 1986).

Some diets for *Trichogramma* contain egg juice from a natural host (Consoli and Parra, 1996). For the egg parasitoid *Edovum puttleri* a homogenate of host eggs (Colorado potato beetle) was used (Hu *et al.*, 1998).

In hymenopterous parasitoids, teratocytes play various roles (Dahlman, 1990), mainly in the exploitation of the host by the parasitoid larva, through secretion of digestive enzymes attacking host tissues or proteins as food for the parasitoid larva (Falabella *et al.*, 2000). *In vitro*, cell products or cell cultures were also used in lieu of hemolymph or of host factors (Grenier *et al.*, 1994).

Diets devoid of insect components

Very few diets are chemically defined. The first defined diet concerning a true parasitoid species was that for *Itoplectis conquisitor* (Yazgan, 1972). Diets of which the entire chemical composition is known, even if the structure of some components is not fully defined (nucleic acids, proteins), can be considered as chemically defined. A small number of diets that fit such a definition were tested successfully for rearing entomophagous insects (Grenier *et al.*, 1994). In such diets, many complex or "crude" components can be added as host substitutes. Irrespective of the species reared, whether parasitoids or predators, the most commonly used components are hen's egg yolk, chicken embryo extract, calf foetal serum, bovine serum, cow milk, yeast extract or hydrolysate, crude proteins or as hydrolysates, meat or liver extracts, and seed oils. For recent reviews of such diets see Thompson (1999) and Thompson and Hagen (1999).

Success in development of some species in artificial conditions

The main successes in artificial mass rearing have been obtained with hymenopterous egg and pupal parasitoids, with tachinid larval parasitoids, and with some polyphagous predators. Extensive general reviews of artificial diets for entomophagous arthropods have been published by Grenier *et al.* (1994), Thompson (1999), and Thompson and Hagen (1999).

Koinobiontic endoparasitic Hymenoptera (parasitoids that do not immediately kill their hosts and where the parasitoid larvae develop in the still living host) are the most difficult species to be reared *in vitro* because the parasitoid has a close relationships with its living host that probably supplies the parasitoid with some specific growth factors necessary for normal development of the parasitoid larva (Greany *et al.*, 1989). Moreover, endoparasitoids for which the diet is not only their food but also their environment for larval development, have special requirements compared to ectoparasitoids or predators. Thus, special attention has to be paid to factors such as osmotic pressure and pH (Grenier *et al.*, 1994).

Quality comparisons of artificially and naturally reared natural enemies

Many parameters used as quality criteria are linked, such as adult body weight and longevity, fecundity, flight activity and searching ability (Kazmer and Luck, 1995). Quality control procedures could be simplified and could thus be made less costly if we were able to use one parameter that is easily measured (e.g. size), to predict the value of another trait that is more complex or time consuming to determine (e.g. fecundity or field performance). In parasitoids, body size may be related with fecundity, longevity, rate of search, and flight ability (Kazmer and Luck, 1995). Bigler (1994) pointed out that the female body size of a parasitoid could be used as an index of fitness or quality parameter, like in *Trichogramma*. But female size is not a reliable parameter to predict field performance when the parasitoids are reared on factitious or artificial hosts. In *Trichogramma* large-sized wasps developed from *in vitro* rearing that showed characteristic abnormalities called "big belly". Despite their large body size, such adults usually have a low viability. The size of a normally shaped *Trichogramma* adult produced *in vitro* is also larger than that of a wasp that developed in the natural host (Nordlund *et al.*, 1997). This is often found in oophagous parasitoids and is the result of a low number of parasitoid eggs developing in the large amount of food that is available to them (Grenier *et al.*, 1995).

In general, the size of *Trichogramma* and other oophagous parasitoids varies according to the number of adults developing in the same host, which consume all the available host material. Remains of the host prevent proper pupation of parasitoids and parasitoid larvae that are excessively large cannot pupate. In a natural situation with too many *Trichogramma* larvae in one host, adult parasitoid size will be reduced accordingly. Under artificial rearing conditions, however, the quantity of food in the artificial host egg is usually very large compared to a natural host egg, and the number of parasitoid eggs laid is often too low for development of normal-sized *Trichogramma* (Grenier *et al.*, 2001).

All parameters related with reproduction are important, and sometimes reproduction capacity can be estimated by a simple measurement, like the body size of the parasitoid, as in *Encarsia formosa* (van Lenteren, 1999). In predators as well, body size is often believed to be a good predictive index of fecundity, but the relationship between both parameters is not always clear. For instance, females of the predatory pentatomid *Podisus maculiventris* reared on an artificial diet were significantly smaller than those fed larvae of *Tenebrio molitor*, but their fecundities were similar (De Clercq *et al.*, 1998a). Rojas *et al.* (2000) obtained females of *Perillus bioculatus* on artificial diet with similar size to that of those offered *Leptinotarsa decemlineata* larvae, but their fecundity was only 10% of that of prey-fed controls. Establishing a relationship between size and predation capacity of a laboratory-produced predator has shown to be even more problematic, even when it is produced on live prey (e.g., De Clercq *et al.*, 1998b). Cohen (2000) reported that *Geocoris punctipes* reared for over 6 years on artificial diet were significantly smaller than feral specimens but had similar predation capacities. Chocorosqui and De Clercq (1999) found that despite their smaller size, artificially reared nymphs of *P. maculiventris* even showed significantly greater predation rates than prey-fed controls.

Several morphological traits and developmental and reproductive parameters which have been used to assess quality of artificially reared parasitoids and predators are reviewed by Grenier and DeClercq (2003).

Quality control aspects of artificially reared natural enemies

Tests for quality comparisons between natural enemies that were reared artificially or on their natural host, were mainly conducted on the first generations after *in vitro* culture, but on rare occasions effects of continuous culture for several generations have been tested (e.g. Hassan and Hagen, 1978; Gao *et al.*, 1982; De Clercq and Degheele, 1992; Nordlund *et al.*, 1997; Cohen, 2000). We suggest that it may not be advisable to maintain entomophagous insects on synthetic diets for many generations, because they may suffer of non-intentional selection inducing a reduction in genetic variability and finally a deterioration of performances. On the other hand, the frequent introduction of new strains to initiate *in vitro* mass production could generate inconveniences such as the necessity for a few generations of laboratory adaptation, the risk of misidentification of the introduced strain or species, and the danger of introducing pathogens or hyperparasitoids (chapters in van Lenteren, 2003).

The ultimate test for quality of entomophagous insects is the assessment of their field efficiency measured as the rate of parasitism or predation (van Lenteren, 2003). However, besides being expensive and time consuming, the complexity of a field setting may obscure the actual causes for the failure or success of natural enemy releases. Therefore, first assessment of the quality of an *in vitro* or *in vivo* produced beneficial will usually be done at a laboratory setting.

Currently, quality control of *in vitro* reared entomophagous insects has been done for the major part only by comparing selected characteristics between *in vitro* and *in vivo* grown insects in the laboratory. Obviously, such comparisons should be done in a fair way, with artificial diets being compared to the best natural rearing protocols. Further, it is important to try to define which parameters should be considered as key criteria to be tested in a first quality assessment of entomophages. Fecundity together with the rate of parasitization in parasitoids and the predation capacity in predators are probably the most relevant criteria to estimate the ultimate quality of a natural enemy.

At the laboratory level, however, such biological parameters could be associated with biochemical parameters as we demonstrated above. We believe that it is worthy to assess these biochemical parameters because, contrary to biological traits, they can be used to suggest modifications of the *in vitro* rearing system, eventually leading to an improvement of the insects produced. Excess or deficiencies of some elements could be balanced by deletion or supplementation of nutritional components in the diet based on a better understanding of the nutritional physiology of an insect. One could say that the insect protein content as a structural element mainly reflects the identity of the species, and the carbohydrate/lipid content as an energy reserve gives an indication of its life potential or fitness.

For the most recent developments in this area: see website IOBC Global under Working Group Artificial Mass Rearing and Quality Control

References

Bigler, F. (1994) Quality control in *Trichogramma* production. In: Wajnberg, E. and Hassan, S.A. (eds.) *Biological Control with Egg Parasitoids*., CAB International, Wallingford, UK, pp. 93-111.

Chocorosqui, V.R. and De Clercq, P. (1999) Developmental and predatory performance of *Podisus maculiventris* (Say) (Heteroptera: Pentatomidae) reared on a meat-based diet. *Mededelingen Faculteit Landbouwkundige en Toepgepaste Biologische Wetenschappen Universiteit Gent* 64, 229-234.

Cohen, A.C. (2000) Feeding fitness and quality of domesticated and feral predators: Effects of long-term rearing on artificial diet. *Biological Control* 17, 50-54.

Consoli, F.L. and Parra, J.R.P. (1996) Biology of *Trichogramma galloi* and *T. pretiosum* (Hymenoptera: Trichogrammatidae) reared *in vitro* and *in vivo*. *Annals of the Entomological Society of America* 89, 828-834.

Dahlman, D.L. (1990) Evaluation of teratocyte functions: an overview. *Archives of Insect Biochemistry and Physiology* 13, 159-166.

De Clercq, P. and Degheele, D. (1992) A meat-based diet for rearing the predatory stinkbugs *Podisus maculiventris* and *Podisus sagitta* (Het.: Pentatomidae). *Entomophaga* 37, 149-157.

De Clercq, P., Merlevede, F. and Tirry, L. (1998a) Unnatural prey and artificial diets for rearing *Podisus maculiventris* (Heteroptera: Pentatomidae). *Biological Control* 12, 137-142.

De Clercq, P., Vandewalle, M. and Tirry, L. (1998b) Impact of inbreeding on performance of the predator *Podisus maculiventris*. *Biocontrol* 43, 299-310.

De Clercq, P. (2004). Culture of natural enemies on factitious foods and artificial diets. *In:* Encyclopedia of Entomology (J. L. Capinera, Ed.). Kluwer Academic Publishers, Dordrecht, vol. I, 650-652.Finney, G.L. and Fisher, T.W. (1964) Culture of entomophagous insects and their hosts. In DeBach, P. (ed.), *Biological Control of Insect Pests and Weeds*. Chapman and Hall, London, pp. 329-355.

Dindo, M.L., Farneti, R., Scapolatempo, M. and Gardenghi, G. (1999) *In vitro* rearing of the parasitoid *Exorista larvarum* (L.) (Diptera : Tachinidae) on meat homogenate-based diets. *Biological Control* 16, 258-266.

Dindo, M.L., Sama, C., Fanti, P. and Farneti, R. (1997) *In vitro* rearing of the pupal parasitoid *Brachymeria intermedia* (Hym.: Chalcididae) on artificial diets with and without host components. *Entomophaga* 42, 445-453.

Falabella, P., Tremblay, E. and Pennacchio, F. (2000) Host regulation by the aphid parasitoid *Aphidius ervi*: the role of teratocytes. *Entomologia Experimentalis et Applicata* 97, 1-9.

Ferkovich, S.M., Moralesramos, J.A., Rojas, M.G., Oberlander, H., Carpenter, J.E. and Greany, P. (1999) Rearing of ectoparasitoid *Diapetimorpha introita* on an artificial diet: supplementation with insect cell line-derived factors. *BioControl* 44, 29-45.

Ferkovich, S.M., Shapiro, J. and Carpenter, J.E. (2000) Growth of a pupal ectoparasitoid, *Diapetimorpha introita*, on an artificial diet: stimulation of growth rate by a lipid extract from host pupae. *BioControl* 45, 401-413.

Gao, Y.G., Dai, K.J. and Shong, L.S. (1982) *Trichogramma* sp. and their utilization in People's Republic of China. In: INRA (ed.) *Les Trichogrammes*. 9, Les colloques de l'INRA, Paris, pp. 181.

Greany, P.D., Vinson, S.B. and Lewis, W.J. (1984) Insect parasitoids: finding new opportunities for biological control. *BioScience* 34, 690-696.

Grenier, S. (1994) Rearing of *Trichogramma* and other egg parasitoids on artificial diets. In: Wajnberg, E. and Hassan, S.A. (eds.) *Biological Control with Egg Parasitoids*., CAB International, Wallingford, UK, pp. 73-92.

Grenier, S. and P. DeClercq 2003. Comparison of Artificially vs. Naturally Reared Natural Enemies and Their Potential for Use in Biological Control. Chapter 9 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 115-131.

Grenier, S., Greany, P.D. and Cohen, A.C. (1994) Potential for mass release of insect parasitoids and predators through development of artificial culture techniques. In: Rosen, D., Bennett, F.D. and Capinera, J.L. (eds.) *Pest Management in the Subtropics: Biological Control - A Florida Perspective*. 10, Intercept, Andover, pp. 181-205.

Grenier, S., Grillé, G., Basso, C. and Pintureau, B. (2001) Effects of the host species and the number of parasitoids per host on the size of some *Trichogramma* species (Hymenoptera: Trichogrammatidae). *Biocontrol Science and Technology* 11, 23-28.

Grenier, S., Yang, H., Guillaud, J. and Chapelle, L. (1995) Comparative development and biochemical analyses of *Trichogramma* (Hymenoptera: Trichogrammatidae) grown in artificial media with hemolymph or devoid of insect components. *Comparative Biochemistry and Physiology* 111B, 83-90.

Hassan, S.A. and Hagen, K.S. (1978) A new artificial diet for rearing *Chrysopa carnea* larvae (Neuroptera, Chrysopidae). *Zeitschrift fürAngewandte Entomologie* 86, 315-320.

Hu, J.S., Gelman, D.B., Bell, R.A. and Loeb, M.J. (1998) *In vitro* rearing of *Edovum puttleri*, an egg parasitoid of the Colorado potato beetle - development from egg through the pupal stage. *BioControl* 43, 1-16.

Kazmer, D.J. and Luck, R.F. (1995) Field tests of the size-fitness hypothesis in the egg parasitoid *Trichogramma pretiosum*. *Ecology* 76, 412-425.

Lenteren, J.C., van (1999) Fundamental knowledge about insect reproduction: essential to develop sustainable pest management. *Invertebrate Reproduction and Development* 36, 1-15.

Lenteren, J.C. van (ed.), 2003. Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. CABI Publishing, Wallingford, UK

Niijima, K., Matsuka, M. and Okada, I. (1986) Artificial diets for an aphidophagous coccinellid, *Harmonia axyridis*, and its nutrition. In: Hodek, I. (ed.) *Ecology of Aphidophaga*., Prague: Academia., pp. 37-50.

Niijima, K., Nishimura, R. and Matsuka, M. (1977) Nutritional studies of an aphidophagous coccinellid, *Harmonia axyridis*. 3. Rearing of larvae using a chemically defined diet and fractions of drone honey-bee powder. *Bulletin of the Faculty of Agriculture of Tamagawa University* 17, 45-51.

Nordlund, D.A., Wu, Z.X. and Greenberg, S.M. (1997) *In vitro* rearing of *Trichogramma minutum* Riley (Hymenoptera: Trichogrammatidae) for ten generations, with quality assessment comparisons of *in vitro* and *in vivo* reared adults. *Biological Control* 9, 201-207.

Rojas, M.G., Morales-Ramos, J.A. and King, E.G. (2000) Two meridic diets for *Perillus bioculatus* (Heteroptera : Pentatomidae), a predator of *Leptinotarsa decemlineata* (Coleoptera : Chrysomelidae). *Biological Control* 17, 92-99.

Singh, P. (1984) Insect diets. Historical developments, recent advances, and future prospects. In: King, E.G. and Leppla, N.C. (eds.) *Advances and Challenges in Insect Rearing*. USDA/ARS, New Orleans, pp. 32-44.

Smirnoff, W.A. (1958) An artificial diet for rearing coccinellid beetles. *Canadian Entomologist* 90, 563-565.

Thompson, S.N. (1999) Nutrition and culture of entomophagous insects. *Annual Review of Entomology* 44, 561-592.

Thompson, S.N. and Hagen, K.S. (1999) Nutrition of entomophagous insects and other arthropods. In: Bellows, T.S. and Fisher, T.W. (eds.) *Handbook of Biological Control: Principles and Applications*. Academic Press, San Diego, CA, pp. 594-652.

Yazgan, S. (1972) A chemically defined synthetic diet and larval nutritional requirements of the endoparasitoid *Itoplectis conquisitor* (Hymenoptera). *Journal of Insect Physiology* 18, 2123-2141.

14. Legislation and regulation of biological control agents

This chapter is based on information presented in van Lenteren & Loomans, 2005; van Lenteren et al., 2006; Loomans & van Lenteren, 2005; see also Appendix 3 and 4

Legal frameworks concerning introduction of exotic species

Various international legal frameworks control the introduction of exotic species from their native ranges to new environments, whether these introductions are deliberate or inadvertent (Fasham & Trumper, 2001; CBD, 2001; Sheppard et al., 2003). Main aim is to prevent the entry, release and/or control of organisms that are harmful, either to animal or to human health, to plant health (IPPC, 1997) or to biodiversity (CBD, 2001; Shine et al , 2000; Genovesi & Shine, 2003). The two main instruments of relevant international legislation with respect to the introduction of exotic organisms are the International Plant Protection Convention (FAO 1951, revised November 1997: IPPC, 1997) and the Convention on Biological Diversity (CBD, 1992). Initially emphasis was on agricultural relevance: releases of biological control agents were largely a management tool for controlling exotic pests with low risks, and attack and survival on native hosts was even considered beneficiary. During the past two decades, however, risks of non-target effects as a result from introductions and releases of exotic organisms for biological pest control are of growing concern to international institutions and national governments. Article 8(h) of the Convention on Biological Diversity - Each Contracting Party shall, as far as possible and as appropriate:.. Prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species – (CBD, 1992) was a turning point. Since then environmental legislation has been implemented by many countries or they are about to do so (OTA, 1993; EC 1992; Sheppard et al, 2003). Decisions by the subsequent Conference of Parties, resulted in advice like formulated in VI/23 (article 10) (COP, 2002): parties and other governments, are urged - when developing, revising and implementing national biodiversity strategies and action plans to address the threats posed by invasive alien species - in implementing the guiding principles, including the precautionary principle.

Most countries with experience in classical biological control, such as Australia, Canada, New Zealand, South-Africa, United Kingdom and the United States, already had legislation and procedures in place to control imports and for analyzing the risks of introducing non-native biological control agents (Sheppard et al., 2003). For those that had not, like most developing countries, the FAO Code of Conduct (FAO, 1997; adopted as ISPM3 by IPPC, 2005) addressed the application of control measures prior to the import and export and introduced procedures of an internationally acceptable level. In particular in countries with little experience in implementing (classical) biological control programs, it supported decision-making and provided a mechanism for formalizing current good practice and facilitation of regional projects (Kairo et al., 2002). However, IPPC provisions applied only where the species concerned was designated as a quarantine pest: it was not explicit about restrictions on pests with environmental impacts and were advisory only (Quinlan et al., 2003). The newly to adopt ISPM3 will become a legally binding standard and has extended its range from classical biological control to inundative biological control, including the use of native natural enemies, microorganisms and other beneficial organisms and is more explicit on environmental impacts of biological control agents (IPPC, 2005). Main areas of relevant legislation in the European Union include the (revised) Plant Health Directive (2000/29/EC) and the Habitat Directive (92/43/EEC) (EC, 2005). The latter requires (article 22) Member States to regulate *the deliberate introduction into the wild of any species which is not native to their territory … so as not to prejudice natural habitats within their natural range or the wild native fauna and flora and, if they consider it necessary, prohibit such introduction.* Member

States need to ensure full compliance with the European legislation, but in many EU-countries regulation is not yet in place.

Instruments: guidelines and standards

Procedures and methods for assessing environmental risks of biological control agents and beneficial organisms are generally, and only indirectly, covered by existing international standards on pest risk analysis. During the past decade, various organizations have developed standards, including guidelines for the export, shipment, import, evaluation and release of biological control agents and beneficial organisms (e.g. EPPO, 1999, 2000; NAPPO, 2001; Sheppard et al., 2003; IPPC, 2005). Evaluation of environmental effects of biological control agents form a central element of these guidelines and a growing number of countries already apply ecological risk assessment (ERA) procedures prior to the import and/or release of a new natural enemy (Sheppard et al., 2003; Bigler et al, 2005; van Lenteren et al., 2006). To facilitate common approaches to decision-making on proposed introductions and avoid unjustifiable trade restrictions, e.g. the Council of Europe advises to work towards a regional or subregional species listing system, preferably based on higher biogeographic (ecoregional) units, consistent with international law (Genovesi & Shine, 2003). With respect to biological control agents white lists already are used in some regions (e.g. EPPO, 2002; ANBP, 2004) and individual countries, but these are, as yet, seldom the result of a thorough environmental risk-assessment procedure. Guidelines and standards mentioned above aim to structure and facilitate procedures and information necessary for a proper risk-assessment, they do not yet provide working instructions for the implementation and risk-assessment itself. For implementation and methodology, see Bigler et al., 2006 and van Lenteren et al., 2006.

Methods for risk analysis

Scientifically based risk-assessment methods are widely accepted as a tool for decision-making, evaluating economic (WTO) and environmental (CDB) costs en benefits (Genovesi & Shine, 2003; IPPC, 2005). Several countries already have developed specific requirements, methods and criteria for environmental risk analysis for biological control agents (Murray, 2002; Bomford, 2003; Sheppard et al., 2003) but in most countries methods are derived from existing pest risk analysis (PRA) protocols developed by regional organizations (EPPO, 1999, 2000; NAPPO, 2001; IPPC, 2005). In others these are based on domestic regulative measures, largely as amendments of legislation en domestic regulation on plant health, pesticide use and/or biodiversity (e.g. DEFRA, 2000). However, there is a large variation between countries in information requirements and evaluation procedures and most of these, if existent at all, are not yet tailored for the intentional release of a biological control agent or beneficial organism. When existent, more ecological information should be used to increase the precision of risk assessment for potential host species (Louda et al., 2003) and both the risks and the benefits of biocontrol applications should be more balanced upon evaluation (Sheppard at el., 2003). In order to develop a more harmonized ERA protocol, the Organisation for Economic Co-operation and Development (OECD) published a *Guidance for Information Requirements for Regulation of Invertebrates as Biological Control Agents* (OECD, 2004), IOBC-WPRS working groups drafted a detailed *Guideline on Information Requirements for Import and Release of Invertebrate Biological Control Agents (IBCAs) in European Countries* (Bigler et al., 2005). This should provide a detailed format for preparation of a dossier supporting an application and assist reviewers (experts and regulators) in a more balanced risk – benefit evaluation of future biocontrol releases. For a recent review of risks related to import and release of exotic biological control agents, see van Lenteren et al., (2006, Annual Review of Entomology) and the chapter “Environmental risk assessment of natural enemies” in this book

Current situation

Twenty countries have implemented regulation for release of biological control agents. Soon, the International Standard for Phytosanitary Measures (ISPM3) will become the standard for all biological control introductions worldwide, but this standard does not provide methods by which to assess environmental risks. A recent review in Annual Reviw of Entomology summarizes documented nontarget effects, and discusses development and application of comprehensive and quick scan environmental risk assessment methods (van Lenteren et al., 2006). Further, a book will appear in 2006 providing a lot of background information and methodologies for environmental risk assessment of natural enemies (Bigler et al., 2006).

For a critical discussion of the politics of assessing risk for biological invasion, see Simberloff (2005).

References

Association of Natural Biocontrol Producers (ANBP). 2004. USDA-APHIS permitted beneficials imported into the USA from other countries as of 27 Feb 2004. Available at: http://www.anbp.org/beneficial%20list.htm

Bigler F, Babendreier D, Kuhlmann U. eds. 2006. Environmental Impact of Invertebrates in Biological Control of Arthropods: Methods and Risk Assessment. Wallingford, UK: CAB Int.

Bigler F, Bale J, Cock MJW, Dryer H., GreatRex, R, Kuhlmann U, Loomans AJM, Lenteren JC van. 2005. *Guideline on information requirements for import and release of invertebrate biological control agents (IBCAs) in European countries*. Report of the IOBC-WPRS Working Group on the Harmonization of Invertebrate Biological Control Agents in Europe.

Bomford M. 2003. Risk assessment for the import and keeping of exotic vertebrates in Australia. Bureau of Rural Sciences, Canberra. 136pp.

Convention on Biological Diversity (CBD). 1992. Convention text. Available at: http://www.biodiv.org/doc/legal/cbd-en.pdf.

Convention on Biological Diversity (CBD). 2001. Review of the efficiency and efficacy of existing legal instruments applicable to invasive alien species. CBD Technical Series no. 2, Montreal, SCBD, 42p. Available at: http://www.biodiv.org/doc/publications/cbd-ts-01.pdf

Convention on Biological Diversity (CBD). 2002. Decisions adopted by the conference of parties to the Convention on Biological Diversity at its sixth meeting, The Hague, 7-19 April 2002. Decision VI/23 - Alien species that threaten ecosystems, habitats or species. http://www.biodiv.org/doc/decisions/COP-06-dec-en.pdf

Department for Environment, Food & Rural Affairs (DEFRA). 2000. The Regulation and Control of the Release of Non-native Animals and Plants into the Wild in Great Britain. A guide to sections 14 and 16 of the Wildlife and Countryside Act 1981. Available at: http://www.defra.gov.uk/environment/gm/nonnav/index.htm

European and Mediterranean Plant Protection Organization. 1999. Safe use of biological control: First Import of exotic biological control agents for research under contained conditions. EPPO Standard PM6/1(1). Available at http://www.eppo.org

European and Mediterranean Plant Protection Organization. 2000. Safe use of biological control: Import and release of exotic biological control agents. EPPO Standard PM6/2(1). Available at http://www.eppo.org

European and Mediterranean Plant Protection Organization (EPPO). 2002. List of biological control agents widely used in the EPPO region - PM6/3(2). Bulletin OEPP/EPPO Bulletin, 32(3): 447-461. Available at http://www.eppo.org/standards/ biocontrol/bio_list.htm

European and Mediterranean Plant Protection Organization (EPPO). - checklist on information required for making a PRA

European Commission (EC). 2005. Habitats Directive (92/43/EEC). Available at http://europa.eu.int/comm/environment/nature/nature_conservation/eu_nature_legislation/habitats_directive/index_en.htm

Fasham M, Trumper K. 2001. Review on non-natives species legislation and guidance. Ecoscope.

Food and Agriculture Organization of the United Nations, 1996. Code of conduct for the import and release of exotic biological control agents. International Standard of Phytosanitary Measures, 3, 23 pp. https://www.ippc.int/IPP/En/default.jsp; https://www.ippc.int/

Genovesi P, Shine C (eds). 2003. European Strategy on Invasive Alien Species. Final Version convention on the conservation of European wildlife and natural habitats. Council of Europe, 23rd meeting Standing

Committee, Strasbourg, 1-5 December 2003. Available at: http://www.coe.int/t/e/Cultural_Co-operation/Environment/Nature_and_biological_diversity/Nature_protection/sc23_tpvs07erev.pdf?L=E

International Plant Protection Convention (IPPC). 1997. International Standards for Phytosanitary Measures. Available at https://www.ippc.int/IPP/En/default.jsp

International Plant Protection Convention (IPPC). 2005. Revision of ISPM No. 3: Guidelines for the export, shipment, import and release of biological control agents and beneficial organisms. Draft for country consultation 2004. International Plant Protection Convention (IPPC). Available at https://www.ippc.int/IPP/En/default.jsp

Kairo MTK, Cock MJW and Quinlan MM. 2003. An assessment of the use of the Code of Conduct for the import and release of exotic biological control agents (ISPM No. 3) since its endorsement as an international standard. Biocontrol News and Information, 24: 15 – 27N.

Lenteren JC van and Loomans AJM. 2006. Environmental risk assessment: methods for comprehensive evaluation and quick scan. In: Bigler F, Babendreier D, Kuhlmann U. eds. Environmental Impact of Invertebrates in Biological Control of Arthropods: Methods and Risk Assessment. Wallingford, UK: CAB Int.

Lenteren JC van, Bale J, Bigler F, Hokkanen HMTand Loomans AJM. 2006. Assessing risks of releasing exotic biological control agents of arthropod pests. Annual Review of Entomology, 51: 609-634.

Loomans AJM and Lenteren JC van. 2005. Tools for environmental risk assessment of invertebrate biological control agents: a full and quick scan method. ISBCA Davos Proceedings. (in press).

Louda SM, Pemberton RW, Johnson MT, Follett PA. 2003. Nontarget effects: the Achilles heel of biological control? Retrospective analyses to reduce risk associated with biocontrol introductions. Annual Review of Entomology, 48: 365-396.

Murray N. 2002. Import Risk Analysis. Animal and Animal products. MAF Biosecurity, New Zealand Ministry of Agriculture and Forestry, 183 pp.

North American Plant Protection Organization 2001. Guidelines for petition for release of exotic entomophagous agents for the biological control of pests. NAPPO Regional Standards for Phytosanitary Measures (RSPM) No. 12. Available at http://www.nappo.org/Standards/OLDSTDS/RSPM12-e.pdf

Organisation for Economic Co-operation and Development (OECD). 2004. Guidance for Information Requirements for Regulation of Invertebrates as Biological Control Agents. OECD Series on Pesticides, 21. Available at http://www.oecd.org/dataoecd/6/20/28725175.pdf

OTA. 1993. Harmful Non-indigenous Species in the United States, Office of Technology Assessment, United States Congress.

Quinlan MM, Mumford JD, Waage JK, Thomas, M. 2003. Proposals for revision of code of conduct. Biocontrol News and Information 24, 1N-3N.

Sheppard AW, Hill R, DeClerck-Floate RA, McClay A, Olckers T, Quimby Jr PC, Zimmermann HG. 2003. A global review of risk-benefit-cost analysis for the introduction of classical biological control against weeds: a crisis in the making? Biocontrol News and Information, 24(4): 91N-108N.

Shine, C, Williams N., Gündling L. 2000. A Guide to Designing Legal and Institutional Frameworks on Alien Invasive Species. IUCN, Gland, Switzerland Cambridge and Bonn. xvi + 138 pp.

Simberloff, D., 2005. The politics of assessing risk for biological invations: the USA as a case study. Trends in Ecology and Evolution, 20: 216-222.

Additional references

Bigler F. 1997. Use and registration of macroorganisms for biological crop protection. Bulletin OEPP/EPPO Bulletin, 27: 95-102.

Lenteren JC van. 1997. Benefits and risks of introducing exotic macro-biological control agents into Europe. Bulletin OEPP/EPPO Bulletin 27: 15-27.

Loomans AJM. 2004. Biologische bestrijders en de Flora- en Faunawet: criteria voor risicoinschatting en toelating biologische bestrijders in Nederland. Gewasbescherming 35(1), 33-37.

National Invasive Species Council (NISC). 2001. Meeting the Invasive Species Challenge. Management Plan for United States, Washington DC. Available at http://www.invasivespecies.gov/council/mpfinal.pdf

National Research Council (NRC). 2002. Predicting Invasions of Nonindigenous Plants and Plant Pests. The National Academic Press, Washington DC. Available at: http://books.nap.edu/

15. Environmental risk assessment of natural enemies

The text of this chapter is based on earlier papers on this topic by van Lenteren et al. 2003, 2006 and 2008.

1. Introduction

In the past 100 years many exotic natural enemies have been imported, mass reared and released as biological control agents for pest control (Albajes et al., 1999; van Lenteren, 2000, 2003; Lynch et al., 2000; USDA, 2001; Mason and Huber, 2002; Copping, 2004). Although the majority of these releases have not resulted in unwanted side effects, some serious cases of non-target hazards by exotic biological control agents against insects and weeds have been recently reported (e.g. Boettner et al., 2000; Follett and Duan, 2000; Wajnberg et al., 2000; Louda et al., 2003; van Lenteren et al., 2006a). Due to the current popularity of biological control, new Invertebrate Biological Control Agents (IBCAs) will become available. To reduce the chance of releasing exotic natural enemies that might pose a risk for the environment, guidelines are being developed to assist in environmental risk assessment.

Various organizations have developed standards, including guidelines for the export, import, shipment, evaluation and release of biological control agents (e.g. EPPO, 2002; IPPC, 2005). Environmental effects of biological control agents form a central element of these guidelines and a growing number of countries already apply risk assessment procedures prior to the import and release of a new natural enemy. Earlier, procedures to assess natural enemies currently used by about 25 countries and codes of conduct or guidelines produced by various organizations were collected, studied and summarized (van Lenteren and Loomans, 2006).Within an EU funded project (van Lenteren et al., 2003) an OECD working group (Anonymous, 2004) and an IOBC Commission (Bigler et al., 2005), guidelines have been developed to harmonize information requirements for import and release of invertebrate biological control agents. Based on all this information, a new comprehensive method for risk assessment was designed (van Lenteren et al., 2006). Subsequently, also a quick scan was developed to be used for natural enemies that are already in use (van Lenteren and Loomans, 2006). As a result of these activities, biological control experts and risk assessors are now provided with the tools for a proper and uniform evaluation of the information provided in the application. In this chapter, I summarize the development of risk assessment procedures for natural enemies, and then describe a stepwise risk assessment procedure.

2. Environmental risk assessment of natural enemies

Risk assessment procedures for biological control agents are usually characterized by questions on four issues:

1. Characterization and identification of biological control agent
2. Health risks

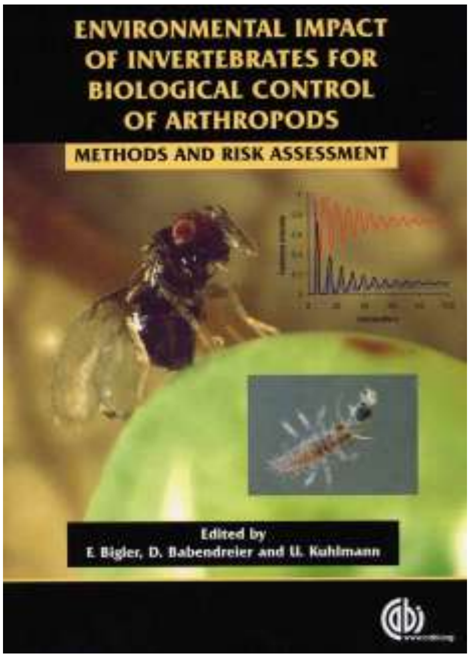
3. Environmental risks
4. Efficacy

The kind of information needed to evaluate these issues are addressed in Anonymous (2004), van Lenteren et al. (2003) and Bigler et al. (2005), and information on the methods to be used to assess non-target effects are addressed in Babendreier et al. (2005) and Bigler et al. (2006). In this chapter, I will concentrate on the third issue, but also shortly address the other issues. Assessment of risks related to releases of natural enemies demands integration of many aspects of their biology, as well as information on ecological interactions. A comprehensive risk assessment comprises the following steps:

1. Identification and evaluation of potential risk of releasing a natural enemy,
2. A plan to minimize risk and mitigate unwanted effects of biological control agents (e.g. Moeed et al., 2006), and
3. A risk/benefit analysis of the proposed release of the natural enemy, together with risk/benefit analyses of current and alternative pest management methods (e.g. Bigler and Kölliker-Ott, 2006).

The last step is essential, because the risk/benefit posed by the release of an exotic natural enemy might particularly be considered acceptable in comparison with the risks posed by other control methods. For definitions of terms used in this chapter, I refer to Anonymous (2003) and Bigler et al. (2006).

2.1 Risk identification and calculation of risk index



Normally, for a risk assessment, one will identify and evaluate the potential negative effects, and determine the probabilities that these will materialize (e.g. Moeed et al. 2006, Bigler et al., 2006). The negative impacts of a biological control agent can be defined as any negative effect, which can be named and measured, such as direct and indirect negative effects on non-target organisms and negative effects on the environment. The risk of negative effects of the release of a biological control agent is the product of the likelihood (L) of impact and the magnitude (M) of impact. The likelihood and magnitude of five groups (ecological determinants) of risks are usually considered in a risk assessment: establishment, dispersal, host range, direct effects, and indirect non-target effects. Next, qualitative scales for likelihood and magnitude need to be described (Table 1), after which one may quantify the scales for likelihood and magnitude (Tables 15.2 and 15.3 in van Lenteren and Loomans, 2006). In an early version of an environmental risk assessment, a numerical value was added to each descriptor of likelihood and magnitude to be able to quantify risk (see van Lenteren et al., 2003). The overall risk index for each natural enemy was obtained by first multiplying the values obtained for likelihood and magnitude, followed by summing-up the resulting values obtained for establishment, dispersal, host range, direct and indirect effects. Based on an evaluation of 31 cases of natural enemy introductions into Europe, the following risk categories were proposed (van Lenteren et al., 2003):

1. Low risk category: for organisms falling in this category, a proposal of no objection against release of the agent can usually be issued;

Table 1. Qualitative scales for likelihood (a), magnitude (b) and level of risk of adverse effects (c) (after Hickson et al., 2000, and van Lenteren and Loomans, 2006).

(a) Likelihood	**Description**
Very unlikely	Not impossible but only occurring in exceptional circumstances
Unlikely	Could occur but is not expected to occur under normal conditions
Possible	Equally likely or unlikely
Likely	Will probably occur at some time
Very likely	Is expected to occur

(b) Magnitude	**Description**
Minimal	Insignificant (repairable or reversible) environmental impact
Minor	Reversible environmental impact
Moderate	Slight effect on native species
Major	Irreversible environmental effects but no species loss, remedial action available
Massive	Extensive irreversible environmental effects

(c) Level of risk of adverse effect

	----------Magnitude----------				
Likelihood	Minimal	Minor	Moderate	Major	Massive
Very unlikely	Insignificant	Insignificant	Low	Medium	Medium
Unlikely	Insignificant	Low	Low	Medium	High
Possible	Low	Low	Medium	Medium	High
Likely	Low	Low	Medium	High	High
Very likely	Medium	Medium	High	High	High

Some natural enemies considered to belong to the high risk category of the first quantitative risk assessment: *Harmonia axyridis* (upper left), *Podisus maculiventris* (upper right), *Hippodamia convergens* (lower left) and *Encarsia pergandiella* (lower right)

2. Intermediate risk category: for organisms falling in this category, the advise will be issued to come up with specific additional information before a conclusion concerning release can be drawn;
3. High risk category: for organisms falling in this category, generally a proposal to not to release the agent will be issued.

Low risk indices were found for many parasitoids, several predatory mites, and one predatory insect. Intermediate risk indices were found for all guilds of natural enemies: parasitoids, predatory insects, predatory mites, parasitic nematodes and entomopathogenic fungi. Entomopathogens (*Beauveria*, *Metarhizium* and *Steinernema*) all score intermediate because of their broad host range, but their very limited dispersal capacities strongly reduce risk. The highest risk indices were found for predatory insects (*Harmonia axyridis* Pallas, *Hippodamia convergens* Guérin-Méneville, *Podisus maculiventris* (Say), *Orius insidiosus* (Say) and parasitoids (*Encarsia pergandiella* (Howard), *Trichogramma brassicae* Bezdenko and *Cales noacki* Howard). This was not a surprise as they would all be classified by biological control experts in the high-risk category based on what is known of their biology.

Because this was the first quantitative risk assessment developed for natural enemies, it was foreseen that the quantification system might have to be adapted based on growing experience. The main problems encountered with this risk assessment were the following:

1. Information for the likelihood and magnitude of all five areas of assessment needed to be available before an evaluation could be made. This makes the assessment in a number of cases unnecessarily costly.
2. The assessment did not identify candidate natural enemies that appear to be clearly unacceptable for import and release based on data for one group of risks early in the process. This should be improved to prevent unnecessary data collection.
3. The numerical values calculated with this assessment did not allow a very clear separation between risk categories. This may result in interpretation and decision making that can easily be manipulated.
4. The overall risk index was obtained by adding five different categories which are in fact not completely independent from each other and should not be rated equally.
5. The overall score of a certain species for a certain ecoregion might lead to establishing an absolute value and unnecessary strict administrative need for measures.

Therefore, a new environmental risk assessment was designed, which is now a stepwise procedure and includes weight factors to solve the problems mentioned above (van Lenteren et al. 2006a, van Lenteren and Loomans, 2006).

2.2 Risk management

The next step of a risk assessment process is to discuss risk management, including risk mitigation and risk reduction. If an exotic biological control agent is expected to cause significant adverse effects on non-target organisms a permit for releases will not be issued. In some cases, risks may be minimized by imposing restrictions concerning for example the types of crops on which the use of the organism is or is not allowed (e.g. treatment of flowering plants with a myco-insecticide), by requesting specific application techniques (e.g. soil incorporation only for insect pathogenic nematodes), or by specifying the ecoregions were the organism is allowed for use (e.g. use of tropical natural enemies in greenhouses in temperate climates).

2.3 Risk/benefit analysis

The last step in making a justified environmental risk analysis for a new biological control agent is to conduct a risk/benefit analysis which should include a comparative performance of pest management methods. The environmental benefits of use of the proposed biological control agent should be compared to environmental effects of currently used and other alternative control methods. Then, the environmental risk analysis is used in the overall risk/benefit assessment where the data concerning characterization, health risks, environmental risks and efficacy of all the control methods for a specific pest will be compared (for details see van Lenteren et al., 2003; 2006a; Bigler and Kölliker-Ott, 2006).

3. Stepwise risk assessment procedure

Recently, as a follow up to the first quantitative risk assessment, an environmental risk assessment method was developed consisting of a stepwise procedure which can be used for all types of invertebrate biological control agents in augmentative and classical biological control, for relevant species or biotypes (e.g. in the case of biotypes that diapause or not, or biotypes with and without wings), whether they are native, established exotics or not yet established exotics (Table 2, summarized in Figure 1; van Lenteren and Loomans, 2006). Native species are included in the evaluation procedure as well, because in cases where natural enemies are released in very large numbers for immediate control of the target pest, like innundative biological control, direct dispersal (overflow, drift) from the release area into the surrounding environment is of main concern for direct non-target effects, irrespective whether the natural enemy species is exotic or not. Contrary to the first quantitative risk assessment described in the previous section, here the decision to advise release or not is taken after each relevant step in the process, thus preventing unnecessary research and resulting in early elimination of clearly risky natural enemies. Definitions for specific terms used in the evaluation process are given in Table 3.

At step 1, exotic and native natural enemies are distinguished. For native natural enemies only one more step (6) in the procedure needs to be followed. Dispersal (step 5) of native agents may be an important issue to be considered in order to address step 6 accordingly. For example, direct and indirect effects of a polyphagous biological control agent may be limited because of very limited dispersal. However, because experimental procedures to establish the dispersal potential of natural enemies might be quite lengthy, this is not included here as a standard procedure for native natural enemies. For exotic natural enemies, whether already present or absent in the target area, more steps need to be followed.

At step 2, natural enemies that are aimed for augmentative biological control (ABC) programs where establishment of the organism in the area of release is not intended, are separated from natural enemies aimed for classical biological control (CBC) where establishment is the aim. For ABC natural enemies one then needs to demonstrate that they cannot establish in step 3.

Table 2. Schedule for an environmental risk assessment of an invertebrate biological control agent. The determinants of the Environmental Risk Index (ERI= Likelihood (L) x Magnitude (M)) should be calculated per step as indicated by van Lenteren et al. (2003) and where appropriate with weight factors as given in Figure 2 (after van Lenteren and Loomans, 2006).

1	Origin – native	GO TO 6
	Origin – exotic, either absent OR present in target area	GO TO 2
2.	Augmentative Biological Control (ABC) programme - establishment not intended	GO TO 3
	Classical Biological Control (CBC) programme - establishment intended	GO TO 4
3.	Establishment unlikely (likelihood L = 1-2) no weight factor included	GO TO 6
	Establishment possible to very likely (L = 3-5), apply magnitude (M) as a weight factor	
	- if risk threshold not crossed (ERI = less than 12)	GO TO 4
	- if risk threshold crossed (ERI = 12 or more)	**NO release**
	(upon request of applicant, GO TO 4)	
4.	If monophagous OR if oligophagous / polyphagous AND only related AND no valued non-targets attacked	**Release**
	If oligophagous / polyphagous AND related and unrelated non-targets attacked AND / OR valued non-targets attacked	**No release**
	(upon request of applicant, GO TO 5)	
5.	Dispersal local (L = 1-2)	GO TO 6
	Dispersal outside target area (L = 3 or more) AND extensive (M 2 or more) apply magnitude (M) as a weight factor	
	- if risk threshold is not crossed (ERI = 5 or less)	GO TO 6
	- if risk threshold is crossed (ERI = 6 or more)	**NO release**
6.	Direct and indirect effects inside dispersal area of natural enemy unlikely (L=1-2) AND at most transient and limited (M = 1-2)	**Release**
	Direct and indirect effects inside ‘dispersal area’ likely (L = 3-5) OR permanent (M = 3-5)	**NO release**

Table 3. Definitions of terms used in environmental risk assessment.

Term	***definition***
exotic	non-indigenous to the country of release
local	restricted to the vicinity (<100m) of the target area (establishment, dispersal)
transient	restricted to only the season of release (establishment, direct and indirect effects)
permanent	effect expected to occur during many seasons/years
monophagous	no non-target species attacked (likelihood = 1)
oligophagous	1-10 non-target species attacked (likelihood = 2 or 3)
polyphagous	>10 species attacked (likelihood = 4 or 5)
related	within same genus

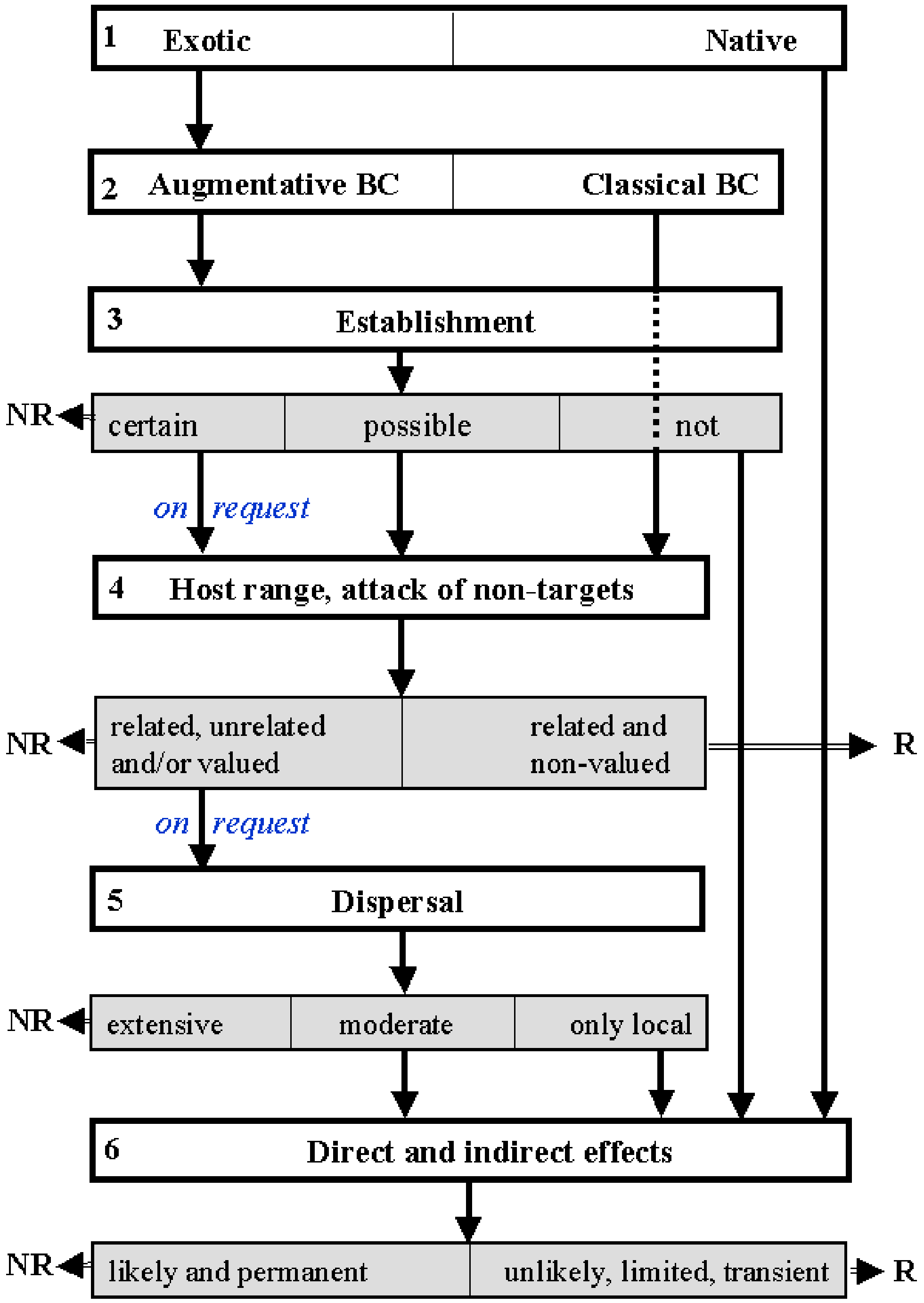


Figure 1. Simplified scheme of an environmental risk assessment of an invertebrate biological control agent. R, NR: release, no release is recommended respectively (after van Lenteren and Loomans, 2006).

If the natural enemy cannot establish (step 3, Likelihood = 1-2), one more step of the procedure (6) needs to be followed. However, if it can establish, the Environmental Risk Index (ERI= Likelihood (L) x Magnitude (M)) should be calculated for establishment (Figure 2a). If a risk threshold is crossed (L = 3-5 AND M = 3-5, Figure 2a), the natural enemy should not be released, and is thus eliminated early in the evaluation process. However, if the applicant desires, he can provide data from studies on host range (step 4), dispersal (step 5) and direct / indirect non-target effects (step 6) and ask for the decision to be reconsidered. If the risk threshold is not crossed, the same procedure needs to be followed as for CBC natural enemies in step 4.

At step 4, the host range issue (see Kuhlmann et al. 2006 and van Lenteren et al., 2006b) is addressed. If the ABC or CBC agent is either monophagous, or oligophagous / polyphagous and attacks only related AND no valued non-targets, i.e. species not of conservation concern, it should be considered for release. On the other hand, if the agent is oligophagous / polyphagous and does attack related and unrelated non-targets AND/OR valued non-targets, the agent should not be considered for release. However, if the applicant desires, he can provide data from studies on dispersal (step 5) and direct/indirect non-target effects and ask for the decision to be reconsidered. In that case, continue with step 5. On request, dispersal can be considered relevant for risk assessment of augmentative releases (see Mills et al., 2006).

At step 5, questions about dispersal of ABC and CBC (where appropriate and on request) agents are addressed. If dispersal is local and mainly in the area of release (L = 1 or 2, see Figure 15.2b in van Lenteren and Loomans, 2006), the procedure can be continued at step 6. But if dispersal is outside the target area (L = 3 or more) AND is extensive (M 2 or more) and thus the environmental risk index (ERI) crosses the value of 6 (Figure 2b), the agent should not be released. If the ERI is 5 or less, the procedure can be continued at step 6.

At step 6, issues related to direct and indirect non-target effects are addressed as releases of exotic agents may negatively affect the abundance of native non-target species or other natural enemies that exploit the same resource (see Messing et al., 2006). If direct and indirect effects inside the 'dispersal area' are unlikely (L = 1-2) AND at most transient and limited (M = 1-2), the agent can be released. However, if direct and indirect effects inside the 'dispersal area' are likely (L = 3-5) OR permanent (M = 3-5), the agent should not be released (Figure 2c).

To calculate risk levels for establishment, dispersal and direct/indirect non-target effects, the criteria are applied as given in van Lenteren et al. (2003), but weight factors are added, and the resulting values can be obtained from Figure 2. If the ERI is below the risk threshold, the value will be in a white box (= continue procedure / release recommended). When the ERI is above the threshold, the value will be in a grey box (= discontinue procedure / no release recommended). Although threshold values as indicated in Figure 2 are currently still largely based on expert judgement, these values need justification and fine-tuning. Here, accuracy and stringency are likely to increase as more data become available through experimental research. The final part of this new risk assessment, i.e. the risk management and the risk/benefit analysis, is the same as described in the previous section.

4. Case study:risk identification and risk indices for *Harmonia axyridis*

In this section, I use the recently designed, risk evaluation methods to evaluate the environmental risks of *Harmonia axyridis* in Northwest Europe.

(a.)

establishment (likelihood)	#	magnitude: local 2^0	<10% 2^1	10-25% 2^2	25-50% 2^3	>50% 2^4 % area
very unlikely	1	n.w.	n.w.	n.w.	n.w.	n.w.
unlikely	2	n.w.	n.w.	n.w.	n.w.	n.w.
possible	3	3	6	12	24	48
likely	4	4	8	16	32	64
very likely	5	5	10	20	40	80

(b.)

dispersal (likelihood) distance	#	magnitude: <1% 2^0	<5% 2^1	<10% 2^2	<25% 2^3	>25% 2^4 % dispersing
<10m	1	n.w.	n.w.	n.w.	n.w.	n.w.
<100m	2	n.w.	n.w.	n.w.	n.w.	n.w.
<1000m	3	3	6	12	24	48
<10000m	4	4	8	16	32	64
>10000m	5	5	10	20	40	80

(c.)

effect (likelihood)	#	magnitude: <5% mort. 2^0	<40% mort. 2^1	>40% mort 2^2	>40% sps 2^3	>40% lps 2^4 effects on nontarget populations
very unlikely	1	n.w.	n.w.	4	8	16
unlikely	2	n.w.	n.w.	8	16	32
possible	3	3	6	12	24	48
likely	4	4	8	16	32	64
very likely	5	5	10	20	40	80

Figure 2. Ecological Risk Index matrix to determine the level of risk of adverse effects of an IBCA for three ecological determinants: establishment (top), dispersal (middle) and direct and indirect effects (bottom). Ecological Risk Indices calculated as Likelihood (L) (vertical) x Magnitude (M) (horizontal) with their respective calculation factors: 1-5 for likelihood, 2^x as a weight factor for magnitude; n.w. = no weight factor included, mort. = mortality, sps = short term population suppression, lps = long term population suppression (see Tables 15.2 and 15.3 for descriptions of determinants). White = below threshold, grey = above threshold (after van Lenteren and Loomans, 2006).

Table 4. Descriptions of likelihood (a) and magnitude (b) for establishment, dispersal, host range, direct and indirect effects (after van Lenteren et al., 2003)

(a) Likelihood	Establishment [1] in non-target habitat	Dispersal[2] potential	Host range[3]	Direct and Indirect effects
Very unlikely	Very unlikely	< 10 m	0 species	Very unlikely
Unlikely	Unlikely	< 100 m	1-3 species	Unlikely
Possible	Possible	< 1,000 m	4-10 species	Possible
Likely	Likely	< 10,000 m	11-30 species	Likely
Very likely	Very likely	> 10,000 m	>30 species	Very likely

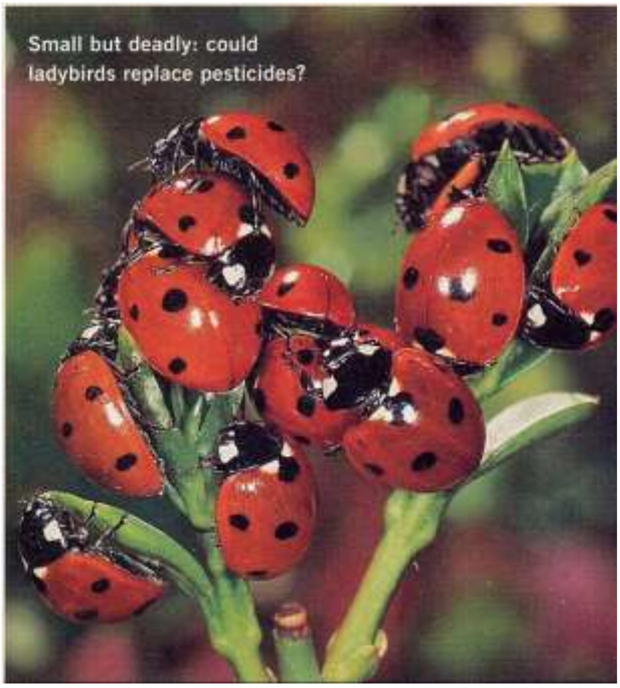
[1] the propensity to overcome adverse conditions and availability of refuges
[2] distance moved per release
[3] the propensity to realise its ecological host range in the release area

(b) Magnitude	Establishment[1] in non-target habitat	Dispersal[2] potential	Host range[3]	Direct[4] and Indirect[5] effects
Minimal	local (transient in time and space)	< 1%	species	< 5% mortality
Minor	<10%	< 5%	genus	< 40% mortality
Moderate	10 - 25%	< 10%	family	> 40% mortality and/or > 10% short term population suppression
Major	25 - 50%	< 25%	order	> 40% short term population suppression, or > 10% permanent population suppression
Massive	>50%	> 25%	phylum	> 40% long term population suppression or local extinction

[1] percentage of potential non-target habitat where biological control agent may establish
[2] percentage of released biological control agent dispersing from target release area
[3] taxon range that biological control agent attacks
[4]direct effect: mortality, population suppression or local extinction of directly affected non-target organisms
[5] indirect effect: mortality, population suppression or local extinction of one or more species of non-target species that are indirectly influenced by the released biological control agent

Table 5. Calculation of risk index for *Harmonia axyridis* made in 2003 with the van Lenteren et al. (2003) approach

	Establ-ishment	Dispers-al	Host range	Direct effects	Indirect effects	Risk indix (sum LxM's)	References
H. axyridis							
Likelihood (L)	5	4	5	5	5		Burgio et al., 2002
Magnitude (M)	4	4	5	4	4		Tedders & Schaefer, 1994
L x M	20	16	25	20	20	101	



4.1. Risk identification and risk index for* H. axyridis *based on the van Lenteren* et al. *(2003) approach.

I use the qualitative scales for likelihood and magnitude presented in Table 1 as a basis. This table was used by van Lenteren et al. (2003) to develop lists of descriptors as a first step towards quantification of risk; these lists are summarized in Table 4. The next step was to give a numerical value to each criterion. For likelihood, very unlikely was given a 1, unlikely a 2, etc.; for magnitude, minimal received a 1, minor a 2, etc. The overall risk index for each natural enemy is obtained by multiplying the figures for likelihood and magnitude, and then by adding the resulting figures obtained for dispersal, establishment, host specificity, direct and indirect effects. The data for *H. axyridis* are summarized in Table 5. Of a possible maximum of 125, the risk index for *H. axyridis* scored 101, and was the second highest value determined for 31 cases presented in the van Lenteren et al. (2003) paper.

4.2 Risk identification, risk index and risk assessment for* H. axyridis *based on the stepwise approach

I will follow the schedule for an environmental risk assessment of an invertebrate biological control agent presented in Table 2 and summarized in Figure 1. *Harmonia axyridis* is an exotic natural enemy (question at step 1), thus we go to step 2. In Northwest Europe, the use of *H. axyridis* was proposed for augmentative releases without the goal to have the biological control agent established, so we go to step 3. The species can establish, which means that the Environmental Risk Index (ERI = likelihood x magnitude) for establishment has to be estimated. Based on literature data summarized in Koch et al. (2006) and own field experience I estimate the likelihood of establishment as “very likely” (the best proof is, of course, that *H. axyridis* has already established in a dozen Northwest European countries (Brown et al, 2008a)). The estimate for magnitude of establishment is that *H. axyridis* will establish in 25-50% of the potential non-target habitats. This estimate is based on field experience in Europe since 2003 which indicates that *H. axyridis* might have spread to and established since in up to 50% of potential non-target habitats. When applying these two estimates to the section on establishment in Figure 2, one comes to an ERI of 40, which would mean that the risk threshold is crossed (the value is in the grey marked section of the figure) and that it should be advised not to release this natural enemy. However, if the producer of natural enemies desires, he can provide data from studies on the host range of the organism (step 4). Let us suppose such data are provided. Host range data from the literature (e.g. Koch et al., 2006 and Loomans, unpublished) show that *H. axyridis* may feed on many aphid species, as well as on numerous other insect prey (e.g. Hemiptera, Psyllidae, Coccoidea, Chrysomelidae, Curculionidae, Coccinellidae and Lepidoptera), spider mites (Tetranychidae), dead insects and also on plant material (e.g. damaged fruit, pollen and nectar). It seems safe to conclude that the organism is highly polyphagous, attacks related and unrelated non-target species and attacks valued non-target species. Thus, the conclusion would once more be that the species should not be released. However, the producer of the biological control agent

might be willing to provide data on dispersal (step 5) and direct/indirect non-target effects (step 6), and ask that the decision to not release be reconsidered. At step 5 questions about dispersal of the species are addressed. Direct and indirect non-target effects might be limited if the species does not leave the area of release. Dispersal data for *H. axyridis* show, however, that the species may cover large distances (up to 442 km per year in North America, McCorquodale, 1998; 50-100 km in Northwest Europe (Brown et al., 2008b, Poutsma et al., 2008) and does move into non-target areas, including nature reserves. This results in an estimate for likelihood of dispersal of more than 10 km per release and for magnitude of dispersal of more than 25% of the released biological control agent from target release area The ERI of 80 for dispersal of this species crosses the threshold (Figure 2) and for the third time the conclusion would be that the species should not be released. But let us continue with the procedure and also try to answer the questions at step 6. The literature provides a number of cases of negative direct and indirect effects in the dispersal area of the species for *H. axyridis*. The species attacks many non-target organisms including beneficial insects and insects of conservation concern (Ware and Majerus, 2008), has resulted in the reduction of populations of native predators in North America, is known as a nuisance in North America and recently also in Northwest Europe, and is a pest of fruit production in North America (e.g. Koch et al., 2006 and references therein). The estimate for likelihood of effects on non-target populations is “very likely”. The most difficult aspect of this whole procedure is to make an estimate for magnitude of non-target effects. Based on all current knowledge, we estimate that the magnitude is between less than 40% mortality of one or more non-target organisms and more than 40% long term population suppression of one or more non-target organisms. Even the lowest estimate results in an ERI of 10 and, thus, the risk threshold is crossed for the fourth time. It is obvious from the information that we have now, that application of this stepwise approach would have led to the very clear conclusion that *H. axyridis* is a potentially risky species for Northwest Europe.

The next step in the risk assessment procedure is to discuss risk management, including risk mitigation and risk reduction. Based on the biology of *H. axyridis*, it can be concluded that there are no easy ways to mitigate or reduce risk (Kenis et al., 2008). It has been suggested to release flightless strains of this predator in order to reduce risk of dispersal into non-target ecosystems (Ferran et al., 1998). Although the flightless strain could result in a significant reduction in dispersal and spread, it does not necessarily reduce its non-target impact. However, the potential consequences of such releases are not yet fully evaluated. Moreover, there are other, native coccinellid species that have a similar capacity for control of aphids.

The last step in making a justified environmental risk analysis for a new biological control agent is to conduct a risk/benefit analysis which should include a comparative performance of pest management methods. In the *H. axyridis* case, current knowledge would lead to the conclusion that, although the predator is capable to effectively control several pest species (a strong benefit; e.g. Landis et al., 2004), its risks are manifold (reduction in population size of native ladybird beetles, attack of many of non-target species, frugivorous behaviour, large aggregations are nuisance to humans, allergic reactions in and biting of humans; e.g. Koch et al., 2006), and it should, thus, not have been released in Nortwest Europe.

4.3 Environmental risk assessment for **H. axyridi***s based on pre-1995 data*

Harmonia axyridis is of Asian origin, is a predator of aphids and other soft bodied arthropods, is frequently associated with trees in natural and agricultural settings when prey is available, but also occurs in herbaceous habitats (Koch et al., 2006). The predator has been used in biological control programs since 1916 in the USA, when the first intentional releases were made in California, with later and more frequent releases in the USA and Canada during the 1970s and 1980s (Gordon, 1985). The ladybird beetle has also been introduced intentionally in Europe, Africa, Central and South America (see Koch et al., 2006 and references therein). Established populations were first detected in North America in 1988 (Chapin and Brou, 1991).

INRA (France) imported *H. axyridis* in 1982. The first intentional, experimental releases were made from 1990 - 1997 in Southeast France followed by commercial releases in France in 1994, and in 1995 in Northwest Europe. Mass production of *H. axyridis* was started in 1992 by the French company Biotop (Kabiri, 2006) and releases of Biotop produced material were made in Northwest Europe since 1995. The first European record of a feral *Harmonia* population originates from 1999, in the town Frankfurt-Niederrad (Germany), where *H. axyridis* releases were made nearby in previous years for aphid control in roses (H. Bathon, personal communication, July 2007), and subsequently many records were made across West European countries (Brown et al., 2008a).

The earliest paper on potential negative side effects of *H. axyridis* dates from 1995 and is from North America (Coderre et al., 1995). Were the biological data about this predator at that time such that one could have concluded it was a highly risky species? To answer this question, I have searched the literature for information about the biology of *H. axyridis* and negative side effects. In the most recent review of the predator by Koch et al. (2006) we found quite a number of papers on *H. axyridis* published before 1995, but most of these concerned taxonomy, distribution patterns and use in biological control. An internet search using Google Scholar with the keywords *Harmonia axyridis* in the title of the paper and for the period before 1995 revealed more than 120 papers. When I combined the species name with risk(s), or nontarget I did not find any paper. As a control, I used risk(s) or nontarget in combination with biological control, and I always found several papers. A check of the more than 120 papers found with *H. axyridis* in the title and published before 1995 showed six papers that might contain information about potential risks. This literature search, together with the pre-1995 papers listed in Koch et al. (2006) and contact with some of the authors of papers resulted in the following information.

1. In a number of papers it is mentioned that *H. axyridis* is a large sized polyphagous predator and has a great reproductive capacity in comparison with other ladybird beetles
2. In some papers, not only the polyphagous habit is mentioned, but also prey species are listed indicating a wide prey range (Vasil'ev, 1963; Hodek, 1973; Iablokoff-Khnzorian, 1982; Schanderl et al., 1985; McClure, 1987)
3. In one paper, the need to explicitly study non-target effects because of the polyphagous habit of *H. axyridis* is mentioned (Coderre et al., 1995)

Based on this, it may be concluded that the potential risk (climate matching and polyphagy, including attack of benficial insects) of *H. axyridis* was clear before the first releases were made in Northwest Europe. In retrospect, this information should have been sufficient to reject import and release of this species, but it was apparently ignored by those who considered release of this predator in Northwest Europe.

This case shows (1) the importance and urgent need of harmonized regulation of biological control agents in Europe, (2) the need of a generally accessible system which provides information on natural enemies that are considered safe or not safe for release in certain ecoregions of Europe, and (3) the requirement of a group of experts which can advise national and international bodies/authorities (e.g. FAO and its regional stations) about the risks of import and release of exotic natural enemies. In the meantime, IOBC has initiated two working groups (one in the IOBC-WPRS region, another under the wings of IOBC Global, see website IOBC Global for more information) to study the benefits and risks of exotic natural enemies. IOBC-WPRS is, in collaboration with the European Plant Protection Organization (EPPO), compiling lists of natural enemies considered safe for release (so-named Positive Lists) as will as lists of risky species.

5. Information on invasive species, both related and not related to biological control

A lot of information on invasive species can be found on issg.org (Invasive Species Specialist Group of the World Conservation Union (IUCN). On this website, a booklet of 100 of the worlds worst invasive alien species is available as pdf in English and French. Species on this list were selected using two criteria: (1) serious impact on biological diversity and/or human activities, and (2) their illustration of important issues of biological invasions. The list of the 100 world's worst invasive species mentions the 5 organisms, all non-arthropod species, that have been released as biological control agents and became pests:

risks biocontrol

A taste for tadpole

They were supposed to fight malaria, but mosquito fish turn out to have other ideas

ONE of the oldest methods of biological control—introducing mosquito fish to eat disease-carrying mosquito larvae—is spawning an environmental disaster. It turns out that the fish prefer eating tadpoles, and this may be a leading cause of the crash in amphibian populations round the world.

"Exotic predators are one of the top three causes of amphibian decline, and mosquito fish are one of these major predators," says Lee Kats of Pepperdine University in Malibu, California. He calls use of the fish "archaic" and says it needs to be re-examined.

Mosquito fish (Gambusia affinis) are native to the US and Mexico. Since early this century governments in the US, Hawaii, Canada, the former Soviet Union, New Zealand and Australia have introduced the fish to exploit their appetite for mosquito larvae.

Feeding frenzy: the fish could be causing the freefall in populations of amphibians like the California treefrog

tadpoles, to replicate natural conditions in Santa Monica's rivers.

The fish had completely undiscerning tastes. They munched their way through all

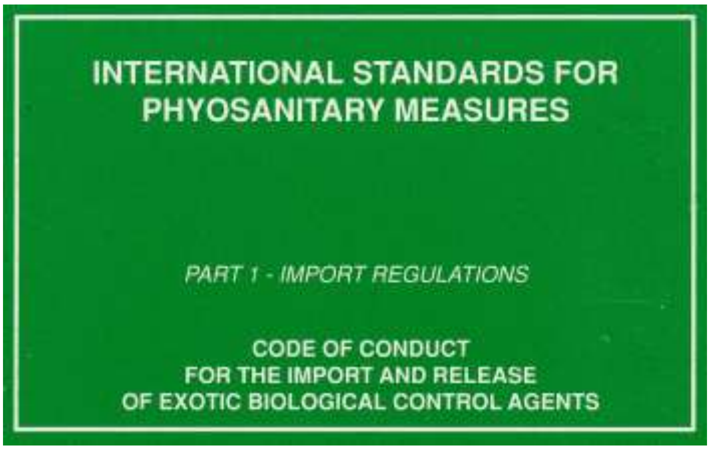
California newts, may be declining because they haven't had time to evolve defences to mosquito fish. Kats believes that the same is probably true for amphibians elsewhere. California treefrogs are already being considered for protected status.

Kats adds that in many places the fish are

Acridotheres tristis	Indian myna bird	
Bufo marinus	Cane toad	
Gambusia affinis	Western mosquito fish	(picture upper left)
Indian mongoose	Herpestes javanicus	
Euglandina rosea	Rosy wolf snail	(picture upper right)

6. Discussion

Recently, methods of risk assessment gradually have shifted, coming from a descriptive, more qualitative framework, largely based on expert judgment in general (e.g. Hickson et al., 2000), via an overall qualitative and quantitative method (van Lenteren et al., 2003) to a stepwise evaluation procedure, using quantitative information when needed and where possible (Bigler et al., 2006; van Lenteren and Loomans, 2006). This not only allows better insight into relevant ecological factors, but also constitutes a more objective approach for evaluating the risks of biological control agents. Methods to determine establishment, dispersal, host range, direct and indirect effects on non- target organisms are discussed in Babendreier et al. (2005)



and Bigler et al. (2006). When we the most recent, stepwise risk assessment procedure was applied to a recent case of an invasive species, i.e. *H. axyridis*, it can be concluded that, based on current knowledge, (1) this predator is a potentially high risk species for Northwest Europe, (2) there are no easy and reliable ways to mitigate or reduce risk of releases of this predator, and (3) a risk/benefit analysis which includes a comparative performance of pest management methods would result in the advice not to release this predator. However, the predator has already been released, is established and is spreading rapidly (Brown et al., 2008a and b). The simple fact that regulation concerning import and release of exotic natural enemies does not exist in some countries and is not well organized in other countries has resulted in this problematic situation (Bigler et al., 2005). As a result, the topic of implementation of a registration procedure for natural enemies is currently hotly debated by the biological control industry, scientists and regulators (Blum et al., 2003; GreatRex, 2003; Hokkanen, 2003; van Lenteren et al., 2003, 2006a; Anonymous, 2004; Bigler et al., 2005; Bigler et al., 2006).


AR REVIEWS IN ADVANCE

ASSESSING RISKS OF RELEASING EXOTIC BIOLOGICAL CONTROL AGENTS OF ARTHROPOD PESTS

J.C. van Lenteren,[1] J. Bale,[2] F. Bigler,[3] H.M.T. Hokkanen,[4] and A.J.M. Loomans[5]

The biological control industry foresees lengthy, cumbersome procedures leading to high costs, and, thus, in some cases, the impossibility to marketing a potentially useful natural enemy because of too high costs. Such costs will strongly depend on the biological and ecological characteristics of a natural enemy. When dealing with a natural enemy that has a very narrow host range, testing and the preparation of a dossier can be limited to about six person months. However, preparation of a dossier for an exotic polyphagous natural enemy that is able to establish, such as *H. axyridis*, could take up to several years, particularly if experiments on dispersal and direct/indirect ecological effects are needed. I estimate that a comprehensive dossier can be appraised in up to six person weeks by governmental agencies. Based on the experience with classical biological control agents reviewed by peers, evaluations, however, take at least six months to complete (Sheppard et al., 2003).

Regulators within ministries of environment and agriculture want to prevent unnecessary and risky releases of exotic organisms, and their concerns have been triggered by the *Harmonia* case. Current activities in the field of regulation will hopefully result in a light and harmonized registration procedure that is not prohibitive for the biological control industry and will result in the pre-selection of safe natural enemies (see e.g. Bigler et al., 2005). A proposed quick scan method for organisms already in use (van Lenteren and Loomans, 2006) should be considered as a kick-start from a situation with no regulations for the use of biological control agents, to one where import and release are regulated to ensure safe use. This quick scan method applied for Northwest Europe resulted in continuation of release of a large number of exotic species. Use of such a quick scan method results in the continuation of ongoing successful and safe biological control programmes, without the risk of returning to chemical control programmes. I estimate that preparation of a dossier for a quick scan will take two person weeks, and appraisal one to six person days per biological control agent. The end result of such a quick scan method applied in various countries may result in lists of species that can be used in certain, specified regions (ecoregions) of the world. These species will be exempted from a comprehensive environmental risk analysis. The availability of regularly updated 'positive lists' might stimulate the application of biological control worldwide.

The case of *Harmonia* releases in Northwest Europe underlines once more that there is an urgent need for harmonized, Europe-wide (indeed global) regulation of biological control agents, including an information system on risky natural enemy species.

Acknowledgements

Horst Bathon (Germany), Giovanni Burgio (Italy), and Eric Lucas (Canada) are thanked for providing important references and information on *H. axyridis*.

References

Albajes R, Gullino, ML., Lenteren, JC van, Elad Y (eds) (1999) Integrated pest and disease management in greenhouse crops. Kluwer Academic Publishers, Dordrecht

Anonymous (2003) Glossary of terms. The second report on harmonisation of risk assessment procedures, Appendix 2 Scientific Steering Committee, European Commission, Brussels

Anonymous (2004) Guidance for information requirements for regulation of invertebrates as biological control agents. OECD Series on Pesticides 21. http://www.oecd.org/dataoecd/ 6/20/28725175.pdf. Cited 4 August 2007

Babendreier D, Kuske S, Bigler F (2003) Parasitism of non-target butterflies by *Trichogramma brassicae* Bezdenko (Hymenoptera: Trichogrammatidae) under field cage and field conditions. Biological Control 26:139-145

Babendreier D, Bigler F, Kuhlmann U (2005) Methods used to assess non-target effects of invertebrate biological control agents of arthropod pests. BioControl 50:821-870

Bigler F, Bale J S, Cock MJW, Dreyer H, GreatRex R, Kuhlmann U, Loomans AJM, Lenteren JC van (2005) Guidelines on information requirements for import and release of invertebrate biological control agents (IBCAs) in European countries. Biocontrol News and Information 26 (4):115N-123N

Bigler F, Babendreier D, Kuhlmann U (eds) (2006) Environmental impact of invertebrates for biological control of arthropods: methods and risk assessment. CAB Int Wallingford

Bigler F, Kölliker-Ott UM (2006) Balancing environmental risks and benefits: a basic approach. In: Bigler F, Babendreier D, Kuhlmann U (eds) Environmental impact of invertebrates for biological control of arthropods: methods and risk assessment. CAB Int Wallingford, pp 273-286

Blum B, Ehlers R, Haukeland-Salinas S, Hokkanen H, Jung K, Kuhlmann U, Menzler-Hokkanen I, Ravensberg W, Strasser H, Warrior P, Wilson M (2003) Letter to the editor. Biological control: safety and regulatory policy. BioControl 48:477-484

Boettner GH, Elkinton JS, Boettner CJ (2000) Effects of a biological control introduction on three nontarget native species of Saturniid moths. Conservation Biology 14:1798-1806

Brown, P.M.J., Adriaens, T., Bathon, H., Cuppen, J., Goldarazena, A., Hägg, T., Kenis, M., Klausnitzer, B.E.M., Kovár, I., Loomans, A.M.J., Majerus, M.E.N., Nedved, O., Perderson, J., Rabitsch, W., Roy, H.E., Temois, V., Zakharov, I.A., Roy, D.B., 2008a. *Harmonia axyridis* in Europe: spread and distribution of a non-native coccinellid. BioControl 53: 5-22.

Brown, P.M.J, Roy, H.E., Rothery, P., Roy, D.B., Ware, R.L., Majerus, M.E.N., 2008b. *Harmonia axyridis* in Great Britain: analysis of the spread and distribution of a non-native coccinellid. BioControl 53: 55- 68.

Burgio G, Santi F, Maini S (2002) On intraguild predation and cannibalism in *Harmonia axyridis* Pallas and *Adalia bipunctata* L. (Coleoptera, Coccinellidae). Biological Control 24:110-116

Chapin JB, Brou VA (1991) *Harmonia axyridis* (Pallas), the third species of the genus to be found in the United States (Coleoptera: Coccinellidae). Proceedings of the Entomological Society of Washington 93:630-635

Coderre D, Lucas E, Gagné, I (1995). The occurrence of Harmonia axyridis (Pallas) (Coleoptera: Coccinellidae) in Canada. Canadian Entomologist 127:609-611

Copping LG (2004) The manual of biocontrol agents. BCPC Publications Sales, 7 Omni Business Centre, Omega Park, Alton, Hampshire

EPPO (2002) List of biological control agents widely used in the EPPO region. PM6/3(2). Bulletin OEPP/EPPO Bulletin 32(3):447-461, http://www.eppo.org/standards/biocontrol/bio_list.htm. Cited 4 August 2007

Ferran A, Giuge L, Tourniaire R, Gambier J, Fournier D (1998) An artificial non-flying mutation to improve the efficiency of the ladybird *Harmonia axyridis* in biological control of aphids. BioControl 43:53-64

Follett PA, Duan JJ (2000) Nontarget effects of biological control. Kluwer Academic Publishers, Dordrecht

Gordon RD (1985) The Coccinellidae (Coleoptera) of America North of Mexico. J New York Entomol Soc 93:1-912

GreatRex R (2003) Comments on the OECD proposal for ‘Guidance for Registration Requirements for Invertebrates as Biological Control Agents’. http://www.ibma.ch/pdf/ comments_on_the_oecd_proposal.pdf. Cited 4 August 2007

Hickson R, Moeed A, Hannah D (2000) HSNO, ERMA and risk management. New Zealand Science Review 57:72-77

Hodek I, (1973) Biology of Coccinellidae. Academia Publishing House, Prague

Hokkanen HMT (2003) Demonstrating the safety of biocontrol. BioControl 48:1

Iablokoff-Khnzorian SM (1982) Les coccinelles; Coléoptères - Coccinellidae. Société Nouvelle des Éditions Boubée, Paris

IPPC (2005) Revision of ISPM No. 3. Guidelines for the export, shipment, import and release of biological control agents and beneficial organisms. International Plant Protection Convention. Draft for country consultation 2004, https://www.ippc.int/IPP/En/default.jsp. Cited 4 August 2007

Kabiri F (2006) Information about production of *Harmonia axyridis* in Europe. http://www.rebeca-net.de/downloads/Risk%20assessment%20macrobials%20Kabiri.pdf. Cited 4 August 2007

Kenis, M., Roy, H.E., Zindel, R., Majerus, M.E.N., 2008. Current and potential management strategies against *Harmonia axyridis*. BioControl 53: 235-252.

Kuske S, Widmer F, Edwards PJ, Turlings TCJ, Babendreier D, Bigler F (2003) Dispersal and persistence of mass released *Trichogramma brassicae* (Hymenoptera: Trichogrammatidae) in non-target habitats. Biological Control 27:181-193

Koch RL, Venette RC, Hutchinson W (2006) Invasions by *Harmonia axyridis* (Pallas)(Coleoptera: Coccinellidae) in the western hemisphere: implications for South America. Neotropical Entomology 35:421-434

Landis DA, Fox TB, Costamagna AC (2004) Impact of multicolored Asian ladybeetle as a biological control agent. American Naturalist 50:153-154

Lenteren, JC van (2000) Measures of success in biological control of arthropods by augmentation of natural enemies. In: Gurr G, Wratten S (eds) Measures of success in biological control. Kluwer Academic Publishers, Dordrecht, pp 77-103

Lenteren JC van (ed) (2003) Quality control and production of biological control agents: theory and testing procedures. CAB Int Wallingford

Lenteren JC van, Babendreier D, Bigler F, Burgio G, Hokkanen HMT, Kuske S, Loomans AJM, Menzler-Hokkanen I, Rijn PCJ van, Thomas MB, Tommasini MG, Zeng Q-Q (2003) Environmental risk assessment of exotic natural enemies used in inundative biological control. BioControl 48:3-38

Lenteren JC van, Bale J, Bigler F, Hokkanen HMT, Loomans AJM (2006a) Assessing risks of releasing exotic biological control agents of arthropod pests. Annual Review of Entomology 51:609-634 + supplemental material

Lenteren JC van, Cock MJW, Hoffmeister TS, Sands DPA (2006b) Host specificity in arthropod biological control, methods for testing and interpretation of the data. In: Bigler F, Babendreier D, Kuhlmann U (eds) Environmental impact of invertebrates for biological control of arthropods: methods and risk assessment. CAB Int Wallingford, pp 38-63

Lenteren JC van, Loomans AJM (2006) Environmental risk assessment: methods for comprehensive evaluation and quick scan. In: Bigler F, Babendreier D, Kuhlmann U (eds) Environmental impact of invertebrates for biological control of arthropods: methods and risk assessment. CAB Int Wallingford, pp 254-272

Lenteren, J.C. van, Loomans, A.J.M., Babendreire, D., Bigler, F., 2008. *Harmonia axyridis*: an environmental risk assessment for Northwest Europe. Biocontrol 53: 37-54.

Louda SM, Pemberton RW, Johnson MT, Follett PA (2003) Nontarget effects: the Achilles heel of biological control? Retrospective analyses to reduce risk associated with biocontrol introductions. Annual Review of Entomology 48:365-396

Loomans AJM (2004) Biologische bestrijders en de Flora- en Faunawet: criteria voor risicoinschatting en toelating biologische bestrijders in Nederland. Gewasbescherming 35(1):33-37

Lynch LD, Hokkanen HMT, Babendreier D, Bigler F, Burgio G, Gao Z-H, Kuske S, Loomans A, Menzler-Hokkanen I, Thomas MB, Tommasini G, Waage J, Lenteren JC van, Zeng, Q-Q (2000) Indirect effects in the biological control of arthropods with arthropods. In: Wajnberg E, Scott JC, Quimby PC (eds). Evaluating indirect ecological effects of biological control. CAB Int Wallingford, pp 99-125

Mason PG, Huber JT (2002) Biological control programmes in Canada, 1981-2000. CAB Int Wallingford

McClure MS (1987) Potential of the Asian predator, *Harmonia axyridis* (Coleoptera: Coccinellidae), to control *Matsuccoccus matsumurae* (Homoptera: Margarodidae) in the United States. Environmental Entomology 16:224-230

McCorquodale DB (1998) Adventive lady beetles (Coleoptera: Coccinellidae) in eastern Nova Scotia, Canada. Entomological News 109(11):15-20

Messing R, Roitberg B, Brodeur J (2006) Measuring and predicting indirect impacts of biological control: competition, displacement and secondary interactions. In: Bigler F, Babendreier D, Kuhlmann U (eds) Environmental impact of invertebrates for biological control of arthropods: methods and risk assessment. CAB Int Wallingford, pp 64-77

Mills NJ, Babendreier D, Loomans AJM (2006) Methods for monitoring the dispersal of natural enemies from point source releases associated with augmentative biological control. In: Bigler F, Babendreier D, Kuhlmann U (eds) Environmental impact of invertebrates for biological control of arthropods: methods and risk assessment. CAB Int Wallingford, pp 114-131

Moeed A, Hickson R, Barratt BIP (2006) Principles of environmental risk assessment with emphasis on the New Zealand perspective. In: Bigler F, Babendreier D, Kuhlmann U (eds) Environmental impact of invertebrates for biological control of arthropods: methods and risk assessment. CAB Int Wallingford, pp 241-253

Poutsma, J., Loomans, A.J.M., Aukema, B., Heijerman, T., 2008. Predicting the potential geographical distribution of the harlequin ladybird, *Harmonia axyridis*, using the CLIMEX model. BioControl 53: 103-126.

Schanderl H, Ferran A, Larroque MM (1985) Les besoins trophiques et thermique des larves de la coccinelle *Harmonia axyridis* Pallas. Agronomie 5:417-422

Sheppard A., Hill R, DeClerck-Floate RA, McClay A, Olckers T, Quimby PC, Zimmermann HG (2003) A global review of risk-benefit-cost analysis for the introduction of classical biological control against weeds: a crisis in the making? Biocontrol News and Information 24:91N-108N

Tedders WL, Schaefer PW (1994) Release and establishment of *Harmonia axyridis* (Coleoptera: Coccinellidae) in the southeastern United States. Entomological News 105:228-243

USDA (2001) The ROBO Database. Available at http://www.ars-grin.gov/nigrp/robo.html. Cited 4 August 2007

Vasil'ev RA (1963) On the bionomics of *Gastrolina thoracica* Baly (Coleoptera, Chrysomelidae. Entomologiceskoe Obozrenie 42(2):264-272 (in Russian)

Wajnberg E, Scott, JC. Quimby PC (2000) Evaluating indirect ecological effects of biological control. CAB Int Wallingford

Ware, R.L., Majerus, M.E.N., 2008. Intraguild predation of immature stages of British and Japanese coccinellids by the invasive ladybird *Harmonia axyridis*. BioControl 53: 169-188.

16. Mistakes and misunderstandings about biological control

In this section I will discuss a number of often heard, but incorrect, statements about biological control. (after: van Lenteren, 1992.)

1. Biological control creates new pests

Use of biological control against one specific pest is said to lead to new pests, due to a termination of spraying with broad-spectrum pesticides. This criticism is often not correct and the reasoning can actually be turned around: application of chemical control results in development of new pests (REFS van Huis and others). Research on biological control begun in order to control pests which were resistant to pesticides. During the early years (1965-1975) of biological control of the key glasshouse pests, spider mite and greenhouse whitefly, new pests did not occur. The new pests which have occurred since 1975 were unintentional imports (e.g. *Spodoptera exigua*, *Liriomyza trifolii*, *L. huidobrensis*, *Frankliniella occidentalis*, *Bemisia tabaci*). These newly imported pests have created serious problems in glasshouses under both biological and chemical control. They threatened the biological control of other pests because natural enemies for them could not always be identified quickly enough. Chemical control of these pests was also very difficult because the pests were already resistant to most pesticides before they were imported into Europe. Several of these pests are now so hard to control chemically that biological control appears to be the only viable option!

2. Biological control is unreliable

The idea that biological control is less reliable than chemical control has emerged mainly as a result of a strong pressure to market natural enemies which were not fully tested for efficacy. This criticism also arose because some non-professional producers of natural enemies did not check whether the agents they sold were effective for control of the target pest. However, the philosophy of most biological control workers is to advocate the use of only those natural enemies which have proven to be effective under practical conditions and within the total pest and disease programme for a certain crop.

Natural enemies for which such efficiency studies were performed, e.g. *Phytoseiulus persimilis*, *Encarsia formosa*, and leafminer parasitoids, have been shown to be as reliable as, or even better than, chemical control agents. Initial difficulties in controlling *Frankliniella occidentalis*, have resulted in a too early large scale usage of predatory mites which have not been tested sufficiently under practical conditions (van Lenteren, 1992). As in chemical control, a period of ten years between the start of research and marketing of an agent is often needed for correct evaluation of a natural enemy.

It is unrealistic to expect that researchers in biological control can solve pest control faster than those working with chemical control. Biocontrol workers often have to deal with much more complex ecological variables than researchers in chemical control. Biological control workers should be careful - even if the pressure is very strong - not to release natural enemies too early resulting in adverse publicity for the technique.

3. Biological control research is expensive

Cost-benefit analyses show that biological control research is more cost effective than chemical control (cost-benefit ratio's of 20:1 for biological control and 5:1 for chemical control (Tisdell, 1990; van Driesche & Bellows, 1995; Neuenschwander, 2001) . The fact that despite this, biological control is not used on a larger scale is mainly due to production and distribution problems of parasitoids and predators: the whole methodology of natural enemy production is very different from that of pesticides, and shelf life of most natural enemies is very short (days or weeks).

It is often thought that finding a natural enemy is more expensive and takes more time than identifying a new chemical agent. The opposite is usually true: costs for developing a natural enemy are on average US$ 2 M and those for developing a pesticide on average US$ 180 M, and both methods usually take an average of 10 years to result in a marketable solution.

4. Application of commercial biological control is expensive for the farmer

An important incentive for the use of biological control in glasshouses has been that the costs of natural enemies have been lower than that of chemical pest control. Ramakers (1992) estimated costs (agent and labour) for chemical and biological pest control in 1980. At that time chemical control of whitefly was twice as expensive as biological control with the parasitoid *E. formosa*. Currently, chemical control of *T. urticae* is almost twice as expensive as biological control with predatory mites (van Lenteren, 1990). Wardlow (1993) found that the costs of biological control of pests in tomato and cucumber in the UK is one fifth to one third that of chemical control. Ramakers (1993) concludes that even the biological control programmes where quite a number of different natural enemies are used (e.g. cucumber), are not more expensive than chemical control programmes. Ramakers (1993) gives the following figures for the costs of biological control in the Netherlands: 0.25, 0.55 and 0.75 US$ m^2 $year^{-1}$ respectively for tomato (4 natural enemies), sweet peppers (6) and cucumber (9). Biological control is now so common in the main crops (tomato, cucumber, egg plant and sweet pepper) that it is sometimes hard to make an estimate for pure chemical control costs.

More general, one should realize that most biological is free of costs! Many naturally occurring beneficial organisms keep pest population below economic thresholds in all natural and agricultural ecosystems worldwide. The very essential ecosystem function of pest control is estimated to have a value of 400 billion US$ per year (Costanza et al., 1997). And it is also important to realize that the benefits of most classical biological control programmes are forgotten once they are effective. It would be nice to have an estimate of the benefits of scale control by *Rodolia* since its start in 1888 !!

5. Practical use of biological control develops very slowly

Also this criticism is incorrect. More than 5,000 introductions of about 2,000 species of exotic arthropod agents for control of arthropod pests in 196 countries or islands have been made during the past 120 years, and more than 150 species of natural enemies (parasitoids, predators and pathogens) are currrently commercially available (van Lenteren et al., 2006). An example of the fast development of biological control: the identification and mass production of natural enemies has been so successful during the past 40 years that there are currently more species of natural enemies available in Northwest Europe (more than 150 species) than there are registered active ingredients for use in insecticides (less than 100).

6. Augmentative biological control does not work

Recently, the following article was published: Collier, T., Steenwyk, R., van, 2004. A critical evaluation of augmentative biological control. Biological Control 31, 245-256. After reading this paper, one might ask why entomologists and biological control researchers have the peculiar habit of self mutilating their work, because the article does not present an evaluation of augmentative releases, instead the authors evaluated some research articles of augmentative biological control. The title is also wrong in that the article is not a critical evaluation of augmentative biological control in general, but is mainly limited to experimental situations in the United States of America. There are, however, plenty examples of successful practical augmentative programs in the USA, as well as outside the USA (see e.g. Gurr and Wratten, 2000, van Lenteren and Bueno, 2003).

Based on the fact that the authors try to answer their research questions with unsuitable data, their answers are in total disagreement with the current state of affairs in the field of augmentative biological control. Augmentative biological control is in many – not all – cases (1) as effective or more effective than chemical pesticide applications, (2) able to achieve target densities often even lower than chemical pesticides can, and (3) has costs lower than or similar to chemical pesticides. In a number of crops, augmentation has completely or in large part replaced broad-spectrum pesticides (see e.g. table 2 in van Lenteren, 1993; van Lenteren, 2000), and this list of crops is growing.

This paper is not an exception, and also at meetings one often hears biological control workers being hypercritical or even saying very negative things about their own field of work. Yes, we need to be critical about bad research and failed projects. But we also need to be clear and positive about the many good results that have been achieved with biological control!

HAVE YOU ENCOUNTERED important and clear cases of wrong criticism of biological control? Please send me a good description of the case and I will include it in this section.

References

Costanza et al., 1997. The value of the world's ecosystem services and natural capital. Nature 387: 253-260.

Gurr, G., Wratten, S. (Eds.), 2000. Measures of Success in Biological Control. Kluwer Academic Publishers, Dordrecht, 429 pp.

Neuenschwander, P., 2001. Biological control of the cassava mealybug in Africa: a review. Biological Control 21: 214-229.

Ramakers, P.M.J., 1982. Biological control in Dutch glasshouses: practical applications and progress in research. Proc. Symp. Integrated Crop Protection. CEC, Valence, France: 265-270.

Ramakers, P.M.J., 1993. More life under glass. In: Zadoks, J.C. (Ed.), Modern Crop Protection: Developments and Perspectives,Wageningen Pers, Wageningen, 91-94.

Tisdell, C.A. 1990. Economic impact of biological control of weeds and insects. In "Critical Issues in Biological Control". M. Mackauer, L.E. Ehler & J. Roland (eds.). Intercept, Andover: 301-316.

van Driesche, R.G. & T.S. Bellows, 1995. Biological Control. Chapman & Hall, New York: 539 pp.

van Lenteren, J.C. 1990. Implementation and commercialization of biological control in West Europe. Int. Symp. on Biological Control Implementation, McAllen, Texas, 4-6 April 1989, NAPPO Bulletin 6 (1990): 50-70.

van Lenteren, J.C. van, 1992. Biological control in protected crops: where do we go? Pesticide Science 36: 321-327

van Lenteren, J.C., 1993. Integrated pest management: the inescapable future. In: Zadoks, J.C. (Ed.), Modern Crop Protection: Developments and Perspectives,Wageningen Pers, Wageningen, 217-225.

van Lenteren, J.C., 2000. A greenhouse without pesticides: fact of fantasy? Crop Protection 19, 375-384.

van Lenteren, J.C., Bueno, V.H.P., 2003. Augmentative biological control of arthropods in Latin America. BioControl 48, 123-139.

van Lenteren, J.C., Bale, J., Bigler, F, Hokkanen, H.M.T., Loomans, A.J.M., 2006. Assessing risks of releasing exotic biological control agents of arthropod pests. Annual Review of Entomology, 51: 609-634.

Wardlow, L.R. Proc. Int. Symp. "Biological Control and Integrated Crop Protection: towards environmentally safer agriculture", Veldhoven, The Netherlands, 8-13 September, 1992.

17. Integrated Pest Management

The references have not yet been checked

Although biological control is the first and preferred line of defense in pest control, often not all pests, diseases or weeds in a certain crop can be kept below damaging levels by biological control alone. Therefore, other pest reducing methods are needed. In this chapter, we make clear that there are many options to integrate other pest management methods with biological control.

What is IPM?

Integrated Pest Management (IPM) is a durable, environmentally and economically justifiable system in which damage caused by pests, diseases and weeds is prevented through the use of natural factors which limit the population growth of these organisms, if needed supplemented with appropriate control measures (van Lenteren, 1993, after Gruys 1976 personal communication). IPM has been defined in many different ways, but the above definition is preferred to make clear that IPM is not just a mix of conventional chemical control with something else. IPM is based on the philosophy that we first need to study which natural pest regulations methods or ecosystem services can be used, before ecosystem disrupting materials like synthetic pesticides are considered. The Food and Agricultural Organization (FAO) of the United Nations agreed on the following description of IPM: " a pest population management system that utilises all suitable techniques in a compatible manner to reduce pest populations and maintains them at levels below those causing economic injury" (Smith & Reynolds 1966).

IPM has received widespread acclaim since the 1950s as the only rational approach to providing long-term solutions to pest problems (Wearing 1988), but the rate of adoption of IPM by farmers have been slow to date. As a main bottleneck limiting progress with IPM worldwide, Wearing (1988) identified problems with the transfer of IPM technology.

IPM is not a technology of the last fifty years. A number of methods to prevent or reduce pests has been in use since the evolution of agriculture (see elements listed in table 1). The new aspects are (1) that the IPM technology was developed in reaction to non-critical and superfluous application of chemical control and (2) the introduction of the concept of economic injury level. A first wave of IPM research took place between 1950 and 1970. Presently we experience a second wave of research interest, which is now supported much wider: policy makers, extension specialists and farmers have realized after a period of euphoria that there are limits to chemical pest control and that durable and safe production of food is possible only if alternatives for pesticides will become available.

Successful IPM programmes have a number of characteristics in common, such as (a) their use was promoted only after a complete IPM programme had been developed covering all aspects of pest and disease control for a crop, (b) an intensive support of the IPM programme by the advisory/extension service was necessary during the first years, (b) the total costs of crop protection in the IPM programme were not higher than in the chemical control programme, and (d) non-chemical control agents (like natural enemies, resistant plant material) had to be as easily available, as reliable, as constant in quality and as well guided as chemical agents.

Why do we need IPM?

To combat pests, diseases and weeds some 800 different chemical ingredients are used in an array of formulations. Insecticides form the most hazardous category of the pesticides because, unlike fungicides and herbicides, they are aimed at killing animal life. The majority of insecticides can be characterized as having a broad-spectrum activity, with well known risks for producers, appliers, consumers and the environment. Several of the fungicides and herbicides have the same drawbacks. These risks are of general concern. However, the main problem for the chemical industry, at present, is the development of resistance against pesticides. The exponential increase of resistance leads to a dramatic rise in human disease problems (e.g. malaria, due to insect-vector resistance) and a decrease in the yields of crops. Furthermore, the development of new pesticides has become increasingly difficult. As many more potential chemicals need to be screened, the overall production costs are rocketing and more research is necessary before new pesticides are legislated (see the introduction to this book). The rate at which insects are developing resistance to new and complex pesticides is, however, not decreasing. Chemical pest control has resulted in more than 500 insect species becoming resistant to one or more pesticides. Almost without exception, attempts to eradicate pest insects have failed. Harmful insects survived all chemical tactics we have invented in order to destroy them.

The above factors, combined, will lead to ever increasing costs for chemical control. As a result, a dramatic decrease in the number of newly marketed insecticides appearing per year has already been experienced over the last two decades: 20 new active ingredients were registered yearly in the sixties, which is in strong contrast to the on average one ingredient being registered per year at present. In relation to the problems just mentioned, the role of agricultural entomologists in pest control will have to change. Since the Second World War many entomologists have been dealing merely with the technical problems of developing, testing and applying insecticides. Much of the information available on the biology of the pest organisms concerned remained unused. Development of ideas on how pests originate and how this may be prevented did not seem necessary when cheap and powerful chemical pesticides were available. Actions which are aimed at the control of individual species, will result in new problems if studies are not done in an holistic ecosystem approach (see next chapter). Inconspicious, but essential changes in the functioning of ecosystems are often only perceived over many years.

Many alternative methods for chemical control are already available (table 1), and we now see increasing interest for these methods which is no longer restricted to scientist but also applies to policy makers at ministries of agriculture and environment (both at the national and international level) and to farmers.

Table 1. Methods to prevent or reduce development of pests (after van Lenteren, 1993)

Prevention:	* prevent introduction of new pests (inspection and quarantine)
	* start with clean seed and plant material (thermal disinfection)
	* start with pest free soil (steam sterilization and solarization)
	* prevent introduction from neighbouring crops
Reduction:	* apply cultural control (crop rotation)
	* use plants which are (partly) resistant to pests
	* apply one of the following control methods:
	- mechanical control (mechanical destruction of pest organisms)
	- physical control (heating)
	- control with attractants, repellants and antifeedants
	- control with pheromones
	- control with hormones
	- genetic control
	- biological control (natural enemies and antagonists)
	- (selective) chemical control

Control based on sampling and spray thresholds: **guided or supervised control**
Control based on the integration of methods which cause the least disruption of ecosystems: **integrated control**

What is the basis for successful implementation of IPM?

In Europe as well as in North America IPM has not put into practice to any great extent until recently, with the exception of greenhouse crops, orchards and corn. Some of the techniques developed for IPM such as development of damage thresholds, pest monitoring techniques (e.g.

with pheromones), selective pesticides etc., however, have been incorporated in to present day pest control programmes (the so-named "supervised" or "guided" control programmes which are based on the principle that spraying is only applied when pest organisms are present and ifit results in economic savings) and have resulted in a more rational use of pesticides. One example may illustrate this point. In the Netherlands the number of growers applying supervised control increased from 8 in 1973 to 700 in 1978 on a total of 4000 farms. This was the result of a special extension programme, completely funded by the government. The implementation of a real IPM programme in Dutch apple orchards followed slowly, but presently special extension programmes help introducing IPM faster. The Dutch Ministry of Agriculture aims at having all orchards under IPM by 1995, and all other crops by 2010. Developments in IPM in Europe are summarized in van Lenteren et al. (1992).

How has implementation been realized?

It is rather easy to develop a set of guideliness for implementation of IPM behind a desk. Each practical situation dictates, however, a number of special aspects for consideration. We have experienced during the past decades that implementation of IPM in some crops (e.g. vegetables in greenhouses in temperate climates) is much easier than in others (e.g. fruit orchards) because of differences in culture methods and composition of the pest and disease complex. Therefore, specific guidelines for implementation of IPM are not presented here, but points are listed to be considered before and during implementation.

Technically, implementation of IPM is not different from that of chemical control. At the introduction of the first IPM programme for a new crop, special attention should be paid to extension. The degree of knowledge makes acceptance of more complicated IPM programmes difficult for the farmer. IPM methods are rather new and demand a different attitude based on the principle to introduce a natural enemy or pesticide only when the pest insect is present and expected to lead to economic loss. A misconception is that such a practice is adopted readily if it is superior to current ones. Only when the IPM method is perceived to be better than conventional methods it will be adopted by growers (Wilson, 1985). The phase of introducing IPM into practice is often neglected. Experience in the Netherlands has shown that the amount of application of IPM is strongly related to the activity and attitude of extension personel. If governmental extension services are weak, IPM will have no chance. All participants in an IPM programme must be receptive to new developments and willing to implement them. In quite a number of countries it is only the scientist who is interested in development of IPM, and often he forgets to check whether others are interested as well. Thus, a lot of IPM work remains ivory tower research. When growers, extension workers and researchers agree that use of IPM is as cheap as chemical control and that production and delivery of alternative control methods is reliable, IPM can be applied in a similar way as chemical control and becomes a normal commercial affair.

For pest and disease control in Dutch greenhouses a cooperative effort of all engaged in crop protection has led in the past 25 years to introduction of virus and fungus resistant plant material, and more than 15 natural enemies against some 20 pests on the main part of the vegetable crops (van Lenteren, 2000). Our growers have learned to rely on biological control and now sometimes ask for new natural enemies before we can provide them with the necessary information. This enthusiasm might, however, create a new problem: a too early release of a natural enemy can result in a bad control effect and thus in negative advertisement for IPM!

Present barriers to practical use of IPM

During the past four decades many countries have invested public money for the development of non-chemical control methods. In this section several reasons are presented why these methods are not used on a much larger scale.

Funding of research in IPM. The results obtained in non-chemical pest control are, of course, in first instance dependent on the amount of research and development work. Funding of this work is limited, especially if one realises the complications of this type of research. Research and development costs in the USA on one aspect of IPM, i.e. biological control, have been less than 20 million US dollars during the period 1917-1972, so less than half a million dollars per year. Costs for research and development for chemical pesticides in only one year, 1973, in the USA were 110 million dollars (data from Sailer 1976).

Very often only limited funding is mentioned as main limitation for implementation. Although it explains part of the story, implementation is most hindered by other constraints, which are discussed below.

Farmers' attitudes. Until very recently, only few farmers (organisations) asked for, or stimulated, development of non-chemical control methods. The adoption of insecticides was rapid because they allowed the farmer to decide when and where they should be used. Decision criteria were clear, the method was easily understood, it was effective (at least in the short term), reduced labour costs, and was a practice the farmer could control and decide upon independently of his neighbours, institutions or agencies. Initially it was a straightforward technology. In contrast, integrated control is more complicated because of the requirement for the monitoring of various pests, the integration of different control methods and situation specific prescriptions. The latter systems require a degree of knowledge and sophistication much greater than pesticide technology demands.

Initiatives for development of IPM programmes were made before and must still come from researchers and policy makers. Being unable to control a pest with chemicals is a stronger reason for farmers to change their ideas on IPM than ideological reasons. As soon as farmers realize that chemical control is no longer sufficient for complete control, their interest for an integrated approach was generated. We should not reproach the farmer for not being interested in IPM, because governments legislate the use of chemicals and often state that when chemicals are used as advised, they do not contaminate food or the environment and do not harm plants, animals or humans. Currently, the attitude of several groups of farmers is changing. European fruit growers and producers of greenhouse vegetables, for example, have experienced the positive aspects of integrated control and seriously worry about the increasing public concern on pesticide usage. Therefore, at present they generally prefer to use IPM methods (van Lenteren and Woets 1988, van Lenteren et al. 1993, van Lenteren 2000).

The viewpoint of the chemical industries. In general, we can state that any complication in a simple chemical pest control programme is appreciated as a negative development by the large industries. Alternatives like biological and genetic control not only complicate chemical control programmes, but they seem to be unattractive commercially as well because of a combination of (van Lenteren 1986):

(a) the impossibility to patent natural enemies,
(b) complicated mass production,
(c) short shelf-life,
(d) specificity (too small market), and
(e) different and more complicated guidance for growers.

Chemical industries will not start the production of other than broad spectrum pesticides on their own initiative, unless the use of those pesticides is prohibited or when pest organisms substantially develop resistance - but time is on our side! We cannot blame the chemical industry for this attitude because their goal is to make a profit. The industry provides pesticides which are allowed for use by a government's legislation and registration policy.

Role of the governments. Therefore, it is the governmental bodies who should be the leaders here and who are in fact the only ones able to change the pest control picture through measures that make some kinds of chemical control less attractive or impossible (by measures concerning registration, taxation, side-effect labelling etc.), and by stimulating other control methods (by funding research, but above all by teaching on all levels in order to change the attitude towards nature, and improvement of the extension service). It is a rather bizarre situation that public money is used for the development of alternatives for chemical control when, at the same time, their application is often not encouraged by governmental bodies, and due to the overall presence of (too) cheap broad-spectrum pesticides.

Vital considerations before starting IPM research and application

Acceptance of integrated control as the official pest control strategy of the country should be the first goal of crop protection researchers. The most important stimulus for an increase in use of IPM is the acceptance by governments of IPM as the main control strategy. If governmental bodies do not support implementation of IPM, activities of researchers should first and only be directed at a change of the policy at high levels. A change in policy should not only be expressed on paper, but has to be materialized in research, education and extension.

Without long-term planning of research and application, IPM programmes are doomed to fail. It is an essential prerequisite that all participants - including extension workers and farmers - in an IPM project are receptive for new developments and are willing to implement them. A goal-oriented, long-term planning of crop protection is necessary to base IPM developmental work on. With a good planning, existing alternative methods can be used to realize a gradual improvement of crop protection.

Introduction of IPM demands a good advisory service. At the introduction of the first IPM programme in a crop, special attention should be paid to extension: the growers have to rediscover the way IPM works and learn to rely on it. For extension workers the problem is that proper guidance of IPM demands considerable biological knowledge and understanding of pests, diseases, weeds and their natural enemies.

Acceptance of IPM as a serious control technology necessitates good public relations and education. Although researchers often do not like to invest time in writing articles that are not for scientific publications, it is essential to do so. Publications in the public press, radio and television programmes are usually more helpful in gaining acceptance for IPM than pure scientific articles. The teaching of crop protection should drastically change at all levels (from vocational schools to university). Presently, often essentially purely technical information is taught on how to spray and with what chemicals. This should partly be replaced with information on other forms of pest control.

The role of the consumer should be exploited to the benefit of IPM. The consumer is generally very receptive to information on control methods not involving chemical pesticides. He is even willing to pay more for non-sprayed produce. Problems with residues on food, accidents with pesticides at production sites and environmental pollution have resulted in a strong awareness of side-effects involved in the use of chemical pesticides. Those working in the field of IPM should now positively react to these attitudes of the consumer.

A serious problem is that consumers often have no direct influence on the production and sale of pesticide free crops. It is the middle man who determines crop quality. Their standards are by no means influenced by the consumer, and their selection criteria result in an overuse of pesticides. It would be to the benefit of farmers and the general public if the last group could have more influence on pesticide-poor or -free production, e.g. by introducing a protected salesmark for food produced under IPM.

Information on integrated control should be provided in the same books and pamphlets of the state advisory service which contain information on chemical control. The first Dutch state guide for pest control (The Crop Protection Guide issued by the Advisory Service and Plant Protection Service (both from the Ministry of Agriculture)) published in 1968 provided no information on biological control. In the 1981 volume (eight's edition) a few lines on biological control were included, more than ten years after the use of *P. persimilis*. The 1991 edition contains 7 pages of information on biological and integrated control out of a total of 605 pages, including lists of pesticides which can safely be used in combination with specific natural enemies. In the most recent edition (2006), biological and integrated control is well covered.

Reliable production of good quality natural enemies should be guaranteed. The past 30 years have been characterized by the appearance and disappearance of natural enemy producers. Only a few producers active in the 1970's are still in the market. The number of beneficials produced is often more than 5-10 million per agent per week (Bolckmans, 2003, van Lenteren & Woets, 1988). Producers have worked hard on quality control methods and, as a result, most of the natural enemies that are now on the market are of good quality (van Lenteren, 2003).

Adaptation of export requirements to make IPM possible. Current export requirements are often unrealistic. They result in overuse of pesticides, with the additional risks of a fast development of resistance, high residue levels and health risks. Within Europe we should work for more realistic requirements, and the first priority should be to change the criterion that products should be without signs of damage, to that of products having no living pest insects.

The future of IPM

IPM is the only long-term solution for crop protection. Agriculture has created a number of environmental problems during the second half of this century. The negative side effects of chemical pest control is one of these problems. It is now generally accepted that alternatives have to be found for several of these pesticides in order to guarantee safe food production. The combination of a number of tactics within IPM programmes, with the aim to reduce or eliminate negative side effects caused by pest control, is the most realistic option for solving this problem. In order to obtain successes in this field, scientists should leave their ivory towers and start to develop empirical integrated control programmes within the framework of integrated farming. That such an approach may lead to much faster reductions in pesticides than the more often followed causal-analytical step-by-step approach is shown, for example, by Wijnands et al. (1993). The past 50 years of research in IPM have been frustrating with regard to the very limited support to have programmes implemented. The recent changes in attitudes of the general public and governments will certainly have a stimulating effect on further development and implementation of IPM.

References (list is far fom complete)

Lenteren, J.C. van, 1986. Parasitoids in the Greenhouse: successes with seasonal inoculative release systems. In: Insect parasitoids: J.K. Waage & D.J. Greathead, eds. Academic Press, London: 341-374.

Lenteren, J.C. van, 1991. Insects, Man and the Environment: Who will survive? In" Environmental Concerns: An Inter-disciplinary Exercise", J.Aa. Hansen (ed.), Elsevier, London : 191-210.

Lenteren, J.C. van, 1993. Integrated pest management: the inescapable future. In "Modern crop protection: developments and perspectives", J.C. Zadoks ed. Wageningen Pers: 217-225.Lenteren, J.C. van, 2000. A greenhouse without pesticides: fact of fantasy? Crop Protection 19:375-384.

Lenteren, J.C. van, A.K. Minks & O.M.B. de Ponti, eds., 1992. Biological Control and Integrated Crop Protection: towards environmentally safer agriculture. Pudoc, Wageningen: 239 pp.

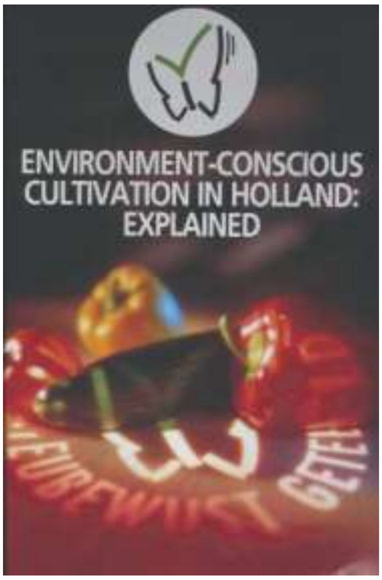
Lenteren, J.C. van and J. Woets, 1988. Biological and Integrated Pest Control in Greenhouses. Annual Review of Entomology 33: 239-269.

Sailer, R.I., 1976. Organisational responsibility for biological research and development inputs, in: Organised Programs to Utilise Natural Enemies of Pests in Canada, Mexico, United States, Animal and Plant Health Inspection Service, USDA, No. 81-28: 10-18.

Smith, R.F. and H.T. Reynolds, 1966. Principles, definitions and scope of integrated pest control. Proceedings FAO Symposium on Integrated Pest Control, Rome, 1965, FAO 1: 11-17.

Wearing, C.H., 1988. Evaluating the IPM implementation process. Annual Review of Entomology 33: 17-38.

Wijnands, F.G., & B.M.A. Kroonen-Backbier, 1993. Management of farming systems to reduce pesticide inputs: the integrated approach. In: Modern Crop Protection: Developments and Perspectives, J.C. Zadoks (ed.). Wageningen Pers, Wageningen, pp. 227-234.



18. Biological and integrated control work better in a systems approach

The references have not yet been checked

Before the large scale application of chemical pesticides, biological control was one of the pest management methods embedded in a system's approach of pest, disease and weed prevention and reduction. A farmer needed to think about pest prevention before he designed his next season's planting scheme and in his choice of crops. He generally made use of three pest management methods: cultural control, host plant resistance and biological control. Cultural methods like crop rotation, cover crops, and sowing and harvesting dates, were used to prevent excessive development of pests (Delucchi, 1987). Plants that had a high degree of resistance or tolerance to pests were another cornerstone of pest prevention. The third cornerstone was formed by natural, classical, inundative and conservation biological control.

After 1945, these methods became redundant as almost all pests could easily be managed by pesticides. As a result, pest control research became highly reductionistic, and changed from a decisive factor in farming design to prevent pests to a mind-numbing but initiallly successful fire-brigade activity. Another effect was that plants were no longer selected for resistance to pests, but only for the highest production of biomass (food) or nicest cosmetic aspects (flowers) and under a blanket of pesticide application. This, on its turn, resulted worldwide in crops that can be considered "incubator plants" being unable to survive without frequent pesticide applications and agro-ecosystems with strongly reduced or exterminated populations of natural enemies .

Now that chemical pesticides are no longer seen as the major solution for lasting pest control, we cannot simply return in a year or so to pre-pesticide pest management methods, as the crops that we currently grow are too weak to survive without pesticides, the natural enemies are no longer present and with farmers who are pesticide addicted. So, first we need to strongly invest in development of new cultivars with resistance to pests and diseases, and this is actually happening (e.g. the Dutch plant breeding industry is now investing 35% of its research money in resistance development, 20 years ago this was only 5%; van Lenteren unpublished). At the same time, we can restore previously used natural, classical, inundative and conservation biological control (e.g. control of spider mites and several insects in apple orchards in several European countries, table 2 in van Lenteren, 1993). Further, several other alternatives for conventional chemical pest control methods can also be implemented, such as mechanical, physical, genetic, pheromonal and semiochemical control. Also, we may manipulate the environment to make it more advantageous to natural enemies. This strategy involves both manipulation of biotic and abiotic elements of the environment and can imply tactics from changing the climate (e.g. greenhouses and wind shields) to applying chemicals stimulating the activity of natural enemies of pests. If natural enemies fail to become established (either due to agricultural practices or to short comings of the adaptability of the natural enemy) or, if established, fail to control the host, manipulation of the natural enemy or its environment may lead to better control. The insect habitat may lack only certain key requisites and addition of these may lead to make the action of natural enemies possible or more effective. Manipulation of the environment is applied on a limited scale, though ther are many opportunities for implementation (see van Lenteren 1987 and Landis et al., 2000 for reviews).

In order to be able to apply these new pest management strategies, we often need to retrain the extension service and farmers in their use. This is all easier said then done, because often we cannot simply replace a certain pesticide with an alternative control method. Instead, we need to return to a systems approach were the influence of all farming activities on pest development are considered. An example of how a systems approach can help is the optimization of fertilizer use (i.e. usually a considerable reduction of fertilizer use) which results in much slower development of several pests like aphids, whiteflies and leafminers. The aim of such an approach is to create a system that is inherently resistant to many pests and, thus, needs fewer or no treatment with conventional pesticides. An important aspect in this approach is farm economics in the form of *maximizing net income*, which is not synonymous with yield maximization. Top yields are obtained with excessively high inputs of fertilizers and pesticides. Reducing the inputs may lead to somewhat lower yields, but financial inputs are also lower and the net income may be the same or better. In farming systems, environmental effects such as pollution of soil and water by pesticides and fertilizers, can be minimized. In general, integrated farming takes more completely into account the various impacts on ecosystems (preservation of flora and fauna, quality and diversity of landscape, and the conservation of energy and nonrenewable resources) as well as sociological considerations (employment, public health and well-being of persons associated with agriculture) than is the case with current farming (Vereijken et al., 1986; Wijnands & Kroonen-Backbier, 1993).

Although research in integrated farming is still very limited, this approach is gaining impetus.The practices which can be manipulated in integrated farming programmes are crop rotation, cultivation, fertilization, pesticide use, cultural control measures, biological control and other alternatives to conventional chemical control. The practical results obtained in a large and long-term project in The Netherlands, are that in integrated farming, an important reduction of environmental pollution is realized through a decrease in fertilizer use and the replacement of chemical pesticides by an intensified knowledge on non-chemical measures (crop rotation, use of resistant varieties). In integrated farming, artificial fertilizers tend to be replaced by organic manure, and the total amount of N is lower to prevent creating a higher sensitivity for pests and diseases. Weed, pest and disease problems are reduced in integrated farming through the use of weed-competitive or disease- and pest-resistant varieties, reduction of N-fertilization, adoption of a specific sowing date and plant spacing, mechanical weed control, natural control, etc. Chemical pest control in integrated farming is based on pest population sampling and use of decision thresholds. A more than 90% reduction in pesticide use was realized consistently in this integrated farming project (van Lenteren, 1997). Integrated farming gave the same economic results as present-day (=conventional) farming. The generally lower physical yields for the integrated system were compensated by cost reduction as a result of the lower input of pesticides and fertilizers. Indirect costs of fertilizer and pesticide use are not yet included in this comparison, which would give an even better result for integrated farming.

A key element of future sustainable crop production will be biological control (van Lenteren, 1998). When we consider the landscape in which agriculture currently takes place, we may conclude that agroecosystems can be characterized by (1) a low species diversity, (2) by plants with little architectural complexity, and (3) by species of plants and animals with a relatively good dispersal ability that are short-lived, produce a large number of offspring and are relatively poor competitors (Bukovinszky, 2004). Further, many agroecosystems are dominated by weeds, insects and pathogens highly adapted for rapid colonization and population increase. Plants with simple architectures have fewer species of insects (pests and beneficials) living on them than diverse and architecturally more complex plant communities (Landis and Marino, 1997). As a consequence of these low-diversity plant and herbivore communities, agroecosystems frequently have strongly impoverished natural enemy communities when compared with natural ecosystems (Landis et al., 2000). Extra-field communities, unless they are also crop fields, are generally less disturbed and architecturally more complex than the crop fields. Richer, more stable extra-field communities may provide relatively stable source populations of beneficial arthropods that facilitate pest management.

But it should be realized that extra-field communities may also provide pest species (Winkler, 2005).

Sustainable pest management must, therefore, be based on an appreciation for how agricultural landscape structure can influence the interactions of extra-field and within-field processes. An understanding of the interchange of organisms and materials between landscape elements and the influence of landscape structure on these interchanges is critical for predicting and managing pest populations in agricultural fields (Lewis et al., 1997). As a starting point, however, it might be more efficient to first concentrate on improvements within cropping systems that could lead to augmentation of natural pest control, and one of these improvements might be multi- or poly-cropping (systems with (a) two or more crop species, (b) with one crop and undergrowth with an economically unimportant plant, or (c) a multicrop consisting of a crop species and herbacious field margins). Although one may come across many publications in which is stated that the natural enemy fauna is richer in multicrops and has a stronger influence on pest insects than in monocultures, very little quantitative and experimental data are available to support such statements (see Vandermeer, 1989, for a review). There is, for example, hardly any information on how natural enemies search for prey in multicrop systems compared with searching in monocultures. However, one of the most often mentioned reasons for multicropping, which is applied on 60% of the world area used for food production, is the protection from pests (Vandermeer, 1989). Pest pressure is lower in multicrops, though not always. The presence of associated plants in the multicrop can lead to attack escape of target crops in three ways, all involving a lower population growth rate of the pest. In one, the associated plants cause plants of the target crop to be less good hosts for the pest (***host-plant quality hypothesis***), in the second, the associated plants interfere directly with activities of the pest (***disruptive-crop hypothesis***), and in the third, the associated plants change the environment so that natural enemies of the pests are favoured (***natural-enemies hypothesis***).

Risch et al. (1983) have tried to identify the mechanisms for reduction of insect herbivores and concluded that in most cases the disruptive-crop hypothesis seemed to explain their findings best, but the natural-enemies hypothesis could also often be used as explanation. Some recent experimental studies indicate that all three hypotheses for pest reduction (the host-plant quality hypotheses (see e.g. Theunissen et al., 1995), the disruptive-crop hypothesis (see e.g. Visser, 1986 and Finch & Kienegger, 1997), and the natural-enemies hypothesis (see e.g. Coll & Bottrell, 1996) may be valid. Other reviews reveal similar results and data clearly show that plant diversity often results in higher natural enemy populations (e.g. Andow, 1983). An analysis of 51 recent studies of habitat manipulation to enhance conservation biological control (Gurr et al., 2000), showed that the vast majority of habitat manipulation projects were successful in showing significant benefits for the natural enemies. However, a significant beneficial effect on natural enemies did not always result in a stronger reduction of pest populations or better yields. Because of the empirical approach that typifies many of these studies until now, effects of agroecosystem diversification on searching behaviour and success of arthropod natural enemies are still poorly understood and need to be studied with priority in order to be able to design fine tuned farming schemes that are based on pest pevention.

References (still need to be checked)

Andow, D.A., 1983. Plant diversity and insect populations: interactions among beans, weeds and insects. PhD thesis, Cornell University, Ithaca, New York.

Bukovinszky, T., 2004. Tailoring complexity: multitrophic interactions in simple and diversified habitats. PhD Thesis, Wageningen University, 161 pp.

Coll, M. and D.G.Bottrell, 1996. Movement of an insect parasitoid in simple and diverse plant assemblages. Ecol. Entomol. 21: 141-149.

Delucchi, V, 1997. Integrated Pest Management: Quo Vadis? Parasitis 1986 Symposium Book, Geneve, Switzerland: 123-166.
Finch, S. & M. Kienegger, 1997. A behavioural study to help clarify how undersowing with clover affects host-plant selection by pest insects of brassica crops. Ent. Exp. Appl. 84: 165-172.
Gurr, G.M., S.D. Wratten & P.Barbosa, 2000. Success in conservation biological control of arthropods. In: Measures of Success in Biological Control, G. Gurr & S. Wratten (eds.). Kluwer Academic Publishers, Dordrecht: 105-132.
Landis, D.A. and P.C. Marino, 1997. Landscape structure and extra-field processes: impact on management of pests and beneficials. In: Handbook of Pest Management, J. Ruberson (ed.),
Marcel Dekker Inc., New York.
Landis, D.A., Wratten, S.D., & Gurr, G.M., 2000. Habitat management to conserve natural enemies of arthropod pests in agriculture. Annual Review of Entomology, 45: 175-201.
Lenteren, J.C. van, 1987. Environmental manipulation advantageous to natural enemies of pests. In: Integrated Pest Management: Quo Vadis? V. Delucchi (ed.). Parasitis 1986 Symposium Book, Geneve, Switzerland, pp. 123-166.
Lenteren, J.C. van, 1993. Integrated pest management: the inescapable future. In "Modern crop protection: developments and perspectives", J.C. Zadoks ed. Wageningen Pers: 217-225.
Lenteren, J.C. van, 1997. From *Homo economicus* to *Homo ecologicus*: towards environmentally safe pest control. In: Modern Agriculture and the Environment, D. Rosen, E. Tel-Or, Y. Hadar, Y. Chen, eds., Kluwer Acadamic Publishers, Dordrecht: 17-31.
Lenteren, J.C. van, 1998. Sustainable and safe crop protection: a reality. Mededelingen van de Faculteit der Landbouwwetenschappen, Universiteit Gent 63(2b): 409-414.
Lewis, W.J., J.C. van Lenteren, S.C. Pathak & J.H. Tumlinson, 1997. A total systems approach to sustainable pest management. Proc. Natl. Acad. Sci. USA, 94: 12243-12248.
Risch, S.J., D. Andow & M.A. Altieri, 1983. Agroecosystem diversity and pest control: data, tentative conclusions, and new research directions. Environ. Entomol. 12: 625-629.
Theunissen, J., C.J.H. Booij & L.A.P. Lotz, 1995. Effects of intercropping white cabbage with clovers on pest infestation and yield. Ent. Exp. Appl. 74: 7-16.
Vandermeer, J., 1989. The Ecology of Intercropping. Cambridge University Press, Cambridge, 237 pp.
Visser, J.H., 1986. Host odor perception in phytophagous insects. Annu. Rev. Entomol. 31: 121-144.
Vereijken, P., C. Edwards, A. El Titi, A. Fougeroux, and M. Way, 1986. Proceedings of Workshop on Integrated Farming, Bulletin I.O.B.C./W.P.R.S. 1986/IX/2, 34 pp.
Wijnands, F.G., & B.M.A. Kroonen-Backbier, 1993. Management of farming systems to reduce pesticide inputs: the integrated approach. In: Modern Crop Protection: Developments and Perspectives, J.C. Zadoks (ed.). Wageningen Pers, Wageningen, pp. 227-234.
Winkler, K., 2005. Assessing the risks and benefits of flowering field field edges: strategic use of nectar sources to boost biological control. PhD Thesis Wageningen University, 118 pp.

19. Books and papers on biological control and IPM

The aim of the literature lists below is to provide information on biological control and IPM. It is far fom complete and meant to be updated regularly. Do you have additions to the list? Please mail references to Joop.vanLenteren@wur.nl, and I will include them in the next version.

IOBC's own journal BioControl, contains peer reviewed papers on biological control of pests, diseases and weeds.

See http://www.springeronline.com/sgw/cda/frontpage/0,11855,5-40109-70-35621340-0,00.html

International Organization for Biological Control of Noxious Animals and Plants (Iobc)

IOBC Newsletter 81
www.IOBC-GLOBAL.org
March 2007

The IOBC Global Newsletter, which appears as PDF site on the IOBC-Global website, regurly has short summaries of new books/ PhD theses on biological control. Books and PhD theses that have been mentioned in the IOBC Global newsletter can all be found on www.IOBC-Global.org, under "Books, PhD theses and Papers on Biological Control".

IOBC OILB WPRS / SROP

The working groups of IOBC-WPRS are producing each year 10-20 bulletins containing the proceedings of their meetings. Bulletins that have appeared since 1993 are listed on the WPRS website, and copies of these bulletins can be ordered with a form available on this website (via www.IOBC-Global.org to WPRS, go to publications etc.). Summaries of the contents of WPRS bulletins can also be found on this website and in Profile, the newsletter of WPRS available as PDF files on the website.

Contents of this chapter

Handbooks and papers on general aspects of biological control

Bellows, T.S & T.W. Fisher, eds., 1999. Handbook of Biological Control. Academic Press, San Diego: 1046 pp. Meant to be a follow up of DeBach 1964, but not reaching the same depth.

Clausen, C.P. 1978 (ed). *Introduced Parasites and Predators of Arthropod Pests and Weeds: A World Review*. Agricultural Handbook No. 480. United States Department of Agriculture, Washington.

Coppel, H.C. & J.W. Mertins, 1977. Biological Insect Suppression. Adv. Series in Agricultural Sciences, No.4, Springer, Berlin: 314 pp. Good book with a different set-up than that of the Californian school (e.g. DeBach (1964) and Huffaker & Messenger (1976).

DeBach, P., ed., 1964. Biological Control of Insect Pests and Weeds. Cambridge University Press, Cambridge: 844 pp. By many considered still the best general book on biological control. Well organized, in depth chapters on the fundamental and applied sides of biological control. Written by well trained biological control researchers of the "previous generation".

Delucchi, V.L., 1976. Studies in Biological Control. Cambridge University Press, Cambridge: 304 pp.

Franz, J.M. ed. 1986. Biological Plant and Health Protection. Fischer, Stuttgart: 341 pp.

Gurr, G., & S. Wratten (eds.), 2000. Measures of Success in Biological Control. Kluwer Academic Publishers, Dordrecht

Hoy, M. & D.C. Herzog eds. 1985. Biological Control in Agricultural IPM Systems. Academic Press, New York: 600 pp. Much attention is given to biotechnology and genetic manipulation.

Huffaker, C.B., ed., 1971, Biological Control. Plenum, New York: 511 pp.

Huffaker, C.B. & P.S. Messenger eds. 1976. Theory and Practice of Biological Control. Academic Press, New York: 788 pp. Although meant to be the successor of DeBach's 1964 book, not all chapters are quite as well written. One of the standard works. History, theoretical backgrounds and practical application are given, as well as an overview of successes and cost/benefit figures for a number of projects.

Krieg, A. & J.M. Franz 1989. Biologische Schaedlingsbekaempfung. Parey, Hamburg: 302 pp. The German textbook on biological control.

Lenteren, J.C. van, A.K. Minks & O.M.B. de Ponti, eds., 1992. Biological Control and Integrated Crop Protection: towards environmentally safer agriculture. Pudoc, Wageningen: 239 pp.

Lenteren, J.C. van, 1993. Biological control of pests. In "Modern crop protection: developments and perspectives", J.C. Zadoks ed. Wageningen Pers: 179-187.

Lenteren, J.C. van, 1993. Parasites and predators play a paramount role in pest management. In: "Pest Management: Biologically Based Technologies", R.D. Lumsden & J.L. Vaughn (eds.). American Chemical Society, Washington DC: 68-81.

Mackauer, M., L.E. Ehler & J. Roland eds. 1990. Critical Issues in Biological Control. Intercept, Andover: 330 pp.

Maxwell, F.G. & F.A. Harris eds., 1974. Proceedings of the Summer Institute on Biological Control of Plant Insects and Diseases. Jackson: University Press of Mississippi.

Ridgway, R.L. & S.B. Vinson ed. 1977. Biological Control by Augmentation of Natural Enemies. Insect and Mite Control with Parasites and Predators. Plenum, New York: 480 pp.

Shternshis M.V., F.S. Djalilov, I.V. Andreeva & O.G. Tomilova. Biologicheskaya zashchita rastenii (Biological plant protection) (Ed. M.V. Shternshis). 2004. Koloss, Moscow: 264 pp. Russian language textbook on biological control of plant pests.

Sweetman, H.L. 1936. The Biological Control of Insects. Comstock Publ. Co. Ithaca, New York: 461 pp. Historically interesting.

Sweetman, H.L., 1958. The Principles of Biological Control. Brown Co., Dubuque: 560 pp. Provides many detailed case studies. Historically interesting.

van Driesche, R.G., & T.S. Bellows, 1996. Biological Control. Chapman & Hall, New York: 539 pp. A good introductury text.

Wood, R.K.S. & M.J. Way eds. 1988. Biological Control of Pests, Pathogens and Weeds: Developments and Prospects. Philosophical Transactions of the Royal Society of London, B, Vol. 318, No. 1189: 376 pp.

Semi-popular books and articles on biological control

DeBach, P., 1974. Biological control by natural enemies. Cambridge University Press, Cambridge: 323. A pleasantly written book which will motivate students to start working in biological control. It does not provide much detail on individual aspects of biological control, but the overview is complete and makes clear what kind of work scientists do and why biological control is important for farmers and the community.

DeBach, P. & D. Rosen, 1991. Biological control by natural enemies, 2nd edition. Cambridge University Press, Cambridge: 440 pp. As in this popular book details are not so important, the first edition (DeBach, 1974) is as informative as this one.

van den Bosch, R. & P.S. Messenger 1973. Biological Control. Insect Educational Publishers, New York: 180 pp.

van den Bosch, R., P.S. Messenger & A.P. Gutierrez 1982. An Introduction to Biological Control. Plenum, London: 230 pp. Update of van den Bosch and Messenger's 1973 book. Suitable for undergraduates.

Waage J. & D.J. Greathead, 1988. Biological control: challenges and opportunities. Phil. Trans. R. Soc. London B, 318: 111-128.

Popular books on biological control

Anonymous, 1969. Leven met insekten: het onderzoek naar een geintegreerde bestrijding van plagen. Pudoc, Wageningen, 177 pp. Overview of the first ten years of research on biological control and integrated pest management of the Working Party on Integrated Control of Pests. (only available in Dutch)

Anonymous, 1980. Landbouw zonder spuit: geïntegreerde bestrijding van insektenplagen in de landbouw. Pudoc, Wageningen, 54. A richly illustrated book for layman explaining biological control and IPM. Overview of the first twenty years of research on biological control and integrated pest management of the Working Party on Integrated Control of Pests. (only available in Dutch)

Moreton, B.D., 1969. Beneficial Insects and Mites. Bull. Min. of Agric., Fish. and Food No. 20. Her Majesty's Stationary Office, London: 118 pp. Good introduction into biological control, excellent illustrations.

Augmentative biological control (inundation and seasonal inoculation)

Lenteren, J.C van, 1988. Implementation of biological control. American Journal of Alternative Agriculture, 3: 102-109.

Lenteren, J.C. van, 1983. Potential of entomophagous parasites for pest control. Agriculture, Ecosystems and Environment 10: 143-158.

Ridgway, R.L. and Vinson S.B. (Eds.) 1977. Biological Control by Augmentation of Natural Enemies: Insect and Mite Control with Parasites and Predators. Plenum, New York.

Classical biological control (inoculation; including case studies)

Booth, R.G.; Cross, A.E.; Fowler, S.V.; Shaw, R.H. (1995). The biology and taxonomy of *Hyperaspis pantherina* (Coleoptera: Coccinellidae) and the classical biological control of its prey, *Orthezia insignis* (Homoptera: Ortheziidae). *Bulletin of Entomological Research* 85, 307-314.

Borgemeister, C.; Holst, N.; Hodges, R.J. (2003) Biological control and other pest management options for larger grain borer *Prostephanus truncatus*. pp. 311–328 in Neuenschwander, P.; Borgemeister, C.; Langewald, J. (eds.) *Biological control in IPM systems in Africa*. Wallingford, Oxon, CAB International.

Kairo, M.T.K.; Pollard, G.V.; Peterkin, D.D.; Lopez, V.F. (2000) Biological control of the hibiscus mealybug, *Maconellicoccus hirsutus* Green (Hemiptera: Pseudococcidae) in the Caribbean. *Integrated Pest Management Reviews* **5**, 241-254.

Tothill, J.D.; Taylor, T.H.C.; Paine, R.W. (1930) *The coconut moth in Fiji. A history of its control by means of parasites.* Imperial Bureau of Entomology, London, UK; 269pp.

Waterhouse, D. F. and K. R. Norris 1987. *Biological Control: Pacific Prospects*. Inkata Press, Australia.

Waterhouse, D. F. 1998. *Biological control of insect pests: Southeast Asian prospects.* ACIAR Monograph No 51, ACIAR Canberra, Australia.

Waterhouse, D. F. 1998. Prospects for the classical biological control of major insect pests and weeds in southern China. *Entomologica Sinica* 5: 320-341.

Conservation biological control

Gurr, G.M., van Emden, H.F. and Wratten, S.D. (1998). Habitat manipulation and natural enemy efficiency: implications for the control of pests. In: *Conservation Biological Control.* Barbosa, P. (ed.). Academic Press, San Diego, 9: 155-183.

Landis, D., Wratten, S.D. and Gurr, G.M. (2000). Habitat Management for Natural Enemies. *Annual Review of Entomology*, 45:175-201.

Landis, D.A., and Wratten, S.D. (2002). Conservation of biological control. In: *Encyclopedia of Pest Management.* D. Pimentel (ed.). Marcel Dekker: New York, 138-140.

Lenteren, J.C. van, 1987. Environmental manipulation advantageous to natural enemies of pests. In: Integrated Pest Management: Quo Vadis? Ed. V. Delucchi. Parasitis 1986 Symposium Book, Geneve, Switzerland: 123-166.

Wäckers, F.L., P.C.J. van Rijn and J. Bruin (eds). Plant-Provided Food for Carnivorous Insects: a protective mutualism and its applications. Cambridge University Press, Cambridge, 11: 326-347.

Wratten, S.D., van Emden, H.F. and Thomas, M.B. (1998). Within-field and border refugia for the enhancement of natural enemies. In: *Enhancing Biological*. C.H. Pickett, and R.L. Bugg (eds). University of California Press, 375-404.

Successes in biological control

Caltagirone, L.E. 1981. Landmark examples in classical biological control. Ann. Rev. Ent. 26: 213-232.
Gurr, G. and Wratten, S.D. (Eds.) (2000). Measures of Success in Biological Control. Kluwer Academic Publishers, Dordrecht, 429 pp.
van Lenteren, J.C., 2000. Measures of success in biological control of arthropods by augmentation of natural enemies. *In* "Measures of success in biological control" (G. Gurr and S. Wratten, Eds.), pp. 77-103. Kluwer Academic Publishers, Dordrecht
Wratten, S.D. and Gurr, G.M. (2000). Synthesis: the future success of biological control. In: *Biological Control: Measures of Success.* G.M. Gurr and S.D. Wratten, S.D. (eds). Kluwer: Dordrecht, 14: 405-416.

History of Biological Control

Cai W.Z., Yan, U.H., Li, L.Y., 2005. The earliest records of insect parasitoids in China. Biological control 32: 8-11.
Gurr, G.M., Barlow, N., Memmott, J., Wratten, S.D. and Greathead, D.J. (2000). A history of methodological, theoretical and empirical approaches to biological control. *Biological Control: Measures of Success.* G.M. Gurr, and S.D. Wratten (eds). Kluwer: Dordrecht, 1: 3-37.
Hagen, K.S., and Franz, J.M., 1973. A history of biological control. In "History of Entomology" (R.F. Smith, T.E. Mittler, and C.N. Smith Eds.), pp. 433-476. Annual Reviews Inc., Palo Alto.
Hirose, Y., 2005. Discovery of insect parasitism and subsequent development of parasitoid research in Japan. Biological Control 32: 49-56.
Lenteren, J.C. van, 2005. Special feature: discovery of the parasitoid lifecycle. Biological Control 32: 1.
Lenteren, J.C. van, 2005. Early entomology and the discovery of insect parasitoids. Biological Control 32: 2-7.
Lenteren, J.C. van & H.C.J. Godfray, 2005. European science in the Enlightenment and the discovery of the insect parasitoid life cycle in The Netherlands and Great Britain. Biological Control 32: 12-24.
Tremblay, E, Masutti, L., 005. History of insect parasitism in Italy. Biological Control 32: 35-39.
Vail, P.V.; Coulson, J.R.; Kauffman, W.C.; Dix, M.E., 2001 History of biological control programs in the United States Department of Agriculture. American Entomologist, 47 (1): 24-49.
Vidal, S., 2005. The history of Hymenopteran parasitoid research in Germany. Biological Control 32: 25-33.

Regional aspects of biological control and country reports

Clausen, C.P. 1956. Biological control of insect pests in the continental United States. USDA Techn. Bull. No. 1139: 151 pp.
Ferrer, F., 2001. Biological control of agricultural insect pests in Venezuela; advances, achievements, and future perspectives. *Biocontrol News and Information* 22.3, 67-74.
Filippov, N.A., 1989. The present status and future outlook of biological control in the USSR. *Acta Entomologica Fennica* 53, 11-18.
Greathead, D.J., 1976. A Review of Biological Control in Western and Southern Europe. CAB, Farnham Royal: 182 pp. Contains an excellent history of biological control in Europe and describes most of the programmes developed for West and South Europe.
Greathead, D.J., 2003. Historical Overview of Biological Control in Africa. In: Biological Control in IPM Systems in Africa, P. Neuenschwander, C. Borgemeister & J. Langewald (eds). CABI Publishing, Wallingford, UK, pp. 1-26.
Jacas, J., P. P. Caballero & J. Avilla (Eds.). 2005. El control biológico de plagas, enfermedades y malas hierbas y la sostenibilidad de la agricultura mediterránea. Publicacions de la Universitat Jaume I. Castelló de la Plana. (In Spanish).
Kelleher, J.S. & M.A. Hulme eds. 1981. Biological control programmes against insects and weeds in Canada 1969-1980. CAB International, Slough: 410 pp. Technical survey of biocontrol projects in Canada.
Lenteren, J.C. van & V.H.P. Bueno, 2003. Augmentative biological control of arthropods in Latin America. BioControl 48: 123-139.
Mason and Greathead Canada
Ooi, P.A.C., Guan-Soon Lim & P.S. Teng, 1992. Biological control: issues in the tropics. Malaysian Plant Protection Society, Kuala Lumpur: 108 pp. Proceedings containing a few interesting papers, particularly the one by D.F. Waterhouse with a very good review of tbe possibilities for biological control in the tropics.
Parra, J.R.P., P.S.M.Botelho, B.S.Corrêa-Ferreira and J.M.S.Bento (eds.) 2002.Controle Biológico no Brasil. Parasitóides e Predadores. Ed. Manole,Sao Paolo, 635p.
Rojas, S., 2005. Biological Pest Control in Chile: History and Future. Libros INIA 12, Ministry of Agriculture, Instituto de Investigaciones Agropecuarias, 125 pp. (In Spanish).
Scott, R.R. ed. 1984. New Zealand Pest and Beneficial Insects. Lincoln Univ. College of Agriculture, Canterbury: 373 pp. A book covering invertebrate pests and beneficial insects in New Zealand.
Shternshis M.V., F.S. Djalilov, I.V. Andreeva & O.G. Tomilova. Biologicheskaya zashchita rastenii (Biological plant protection) (Ed. M.V. Shternshis). 2004. Koloss, Moscow: 264 pp. (In Russian).

Shumakov, E.M., Gusev, G.V. & Fedorinchik, N.S. (eds.) 1974. Biological agents for plant protection. Moscow, Kolos, 490 pp. (Original version in Russian, translated in 1974 by USDA, Washington).
Waterhouse, D.F. & K.R. Norris 1987. Biological Control: Pacific Prospects. Inkata Press, Melbourne: 454 pp. Rather technical book on the biological control of insect pests in the South Pacific and can be used for identifying target pests and weeds. Gives a short introduction on biological control and mainly consists of a listing of the main pests in the South Pacific and the opportunities for biological control.
Waterhouse, D. F. and D. P. A. Sands 2001. Classical biological control of arthropods in Australia. ACIAR Monograph No. 77, ACIAR Canberra, Australia.
Zapater, M.C. (Ed.) 1996. El Control Biológico en América Latina. IOBC, Buenos Aires.

Biology of natural enemies

Clausen, C.P., 1940. Entomophagous Insects. McGraw-Hill, New York: 688 pp. Very comprehensive book on natural enemies of insects. No later book has even approached it. The taxonomy has of course somewhat changed.
Clausen, C.P. ed. 1978. Introduced Parasites and Predators of Arthropod Pests and Weeds: a World Review. USDA/ARS, Agricultural Handbook No. 480, Washington: 545 pp. Gives a reliable record over about 80 years (1880 - 1968) of what beneficial species have been colonized world wide, together with information on whether or not the species became established. So it records failures as well as successes. Arthropod pests and weeds are discussed. The most thorough resume of biological control efforts and successes
Huffaker, C.B. & R.L. Rabb eds. 1984. Ecological Entomology. Wiley, New York: 844 pp.
Pristavko, V.P. (ed.) 1975. Insect behavior as a basis for developing control measures against pests of field crops and forests. Naukova Dumka Publishers, Kiev, 238 pp. (Original version in Russian, translated in 1981 by USDA, Washington)

Biology of parasitoids

Ardeh, M.J., P.W. de Jong, J.C. van Lenteren, 2005. Intra- and interspecific host discrimination in arrhenotokous and thelytokous *Eretmocerus* spp. Biological Control 32: 74-80.
Askew, R.R., 1971. Parasitic Insects. Heinemann, London: 316 pp. Book dedicated purely to parasitic insects. In depth overview, beautiful illustrations.
Austin, A. D. and M. Dowton (eds.), 2000. Hymenoptera Evolution, Biodiversity and Biological Control. CSIRO, Melbourne, Australia.
Bukovinszky, T., Gols, T., Posthumus, M.A., van Lenteren, J.C. and Vet, L.E.M, 2005. Variation in plant volatiles and attraction of the parasitoid *Diadegma semiclausum* (Hellén). Journal of Chemical Ecology 31: 461- 480.
Burger, J.M.S., T.M. Reijnen, J.C. van Lenteren & L.E.M. Vet, 2004. Host feeding in insect parasitoids: why destructively feed upon a host that excretes an alternative? Entomologia Experimentalis et Applicata 112: 207-215.
Doutt, R.L., 1959. The biology of parasitic Hymenoptera. Annu. Rev. Entomol. 4: 161-182. Information overlaps with that in Doutt's chapter in DeBach's 1964 book.
Doutt, R.L., 1964. **** titel. In: DeBach, P. ed., 1964. Biological Control of Insect Pests and Weeds. Cambridge University Press, Cambridge: pp.
Godfray, H.C.J. (1994) *Parasitoids. Behavioral and evolutionary ecology* Princeton University Press, Princeton, New Jersey.
Lenteren, J.C. van & K. Bakker, 1975. Discrimination between parasitised and unparasitised hosts in the parasitic wasp *Pseudeucoila bochei*: a matter of learning. Nature 254, no.5499: 417-419.
Lenteren, J.C. van, K. Bakker & J.J.M. van Alphen, 1978. How to analyse host discrimination. Ecological Entomology 3: 71-75.
Lenteren, J.C. van, 1981. Host discrimination by parasitoids. In: Semiochemicals: their role in pest control. Ed. D.A.Nordlund, R.L. Jones & W.J. Lewis. Wiley and Sons, New York: 153-179.Waage, J.K., & M.P. Hassell, 1982. Parasitoids as biological control agents - a fundamental approach. Parasitology 84: 241-268.
Lenteren, J.C. van, 1999. Fundamental knowledge about insect reproduction is essential to develop sustainable pest management. Invertebrate Reproduction and Development, 36: 1-15.
Lewis, W.J., L.E.M. Vet, J.H. Tumlinson, J.C. van Lenteren & D.R. Papaj, 2003. Variations in natural-enemy foraging behaviour: essential element of a sound biological-control theory. Chapter 4 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 41-58.
Quicke, D.L.J. (1997) Parasitic wasps. Cambridge University Press.
Vet, L.E.M., W.J. Lewis, D.R. Papaj and J.C. van Lenteren, 2003. A variable-response model for parasitoid foraging behaviour. Chapter 3 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 25-39.

Waage, J.K., & D.J. Greathead, eds., 1986. Insect parasitoids: Academic Press, London
Winkler, K., Waeckers, F.L., Bukovinszkine-Kiss, G., Lenteren, J.C. van, 2005. Nectar resources are vital for *Diadegma semiclausum* fecundity under field conditions. Basic and applied ecology, in press

Biology of predators

Hoy, M.A., G.L. Cunningham & L. Knutson (Eds.) 1983. Biological Control of Pests by Mites. Division of Agricultural Sciences, University of California, Publ. 3304.

Biology of insect pathogens and microbial insect control

Burges, H.D. ed. 1981. Microbial control of pests and plant diseases 1970-1980. Academic Press, London: 949 pp. Continues from, and complements, Burges adn Hussey (1971)
Burges, H.D. & N.W. Hussey eds. 1971. Microbial control of insects and mites. Academic Press, London: 861 pp. Comprehensive review of microbials.
Cantwell, G.E. ed. 1974. Insect diseases. Marcel Dekker, New York, 2 Vols: 595 pp. Provides detailed information on the wide range of diseases affecting insects, and the ways in which these can be manipulated for pest control.
DaSilva, E.J., Y.R. Dommergues, E.J. Nyns & C. Ratledge. Microbial technology in the developing world. Oxford University Press, Oxford: 444 pp. Contains a chapter by H.D. Burges reviewing the present use of insect pathogens (bacteria, viruses and fungi) in pest control and their potential use in developing countries.
DeBach, P. ed 1964. Biological Control of Insect Pests and Weeds. Cambridge University Press, Cambridge. Chapters 18-21
Federici, B.A., 1999. A perspective on pathogens as biological control agents for insect pests. *In* "Handbook of Biological Control" (T.S. Bellows and T.W. Fisher, Eds.), pp. 517-548. Academic Press, San Diego.
Fuxa J.R. & Y. Tanada eds 1979. Epizootiology of Insect Diseases. Wiley, New York.
Kurstak, E. ed. 1982. Micriobial and Viral Pesticides. Dekker, New York.
Maramorosch, K. & K.E. Sherman eds. 1985. Viral Insecticides for Biological Control. Academic Press, Orlando: 809 pp. This books brings together basic and applied aspects of viruses as natural enemies of insects.
Meekes, E.T.M, J.J. Fransen & J.C. van Lenteren, 2002. Pathogenecity of *Aschersonia* spp. against whiteflies *Bemisia argentifolii* and *Trialeurodes vaporariorum*. Journal of Invertebrate Pathology 81: 1-11.
Moscardi, F., 1999. Assessment of the application of baculoviruses for control of Lepidoptera. *Annu. Rev. Entomol.* 44, 257-289.Payne, C.C., 1988. Pathogens for the control of insects: where next? Phil. Trans. R. Soc. London, 13, 318: 225-248. Excellent review article, survey of all groups of pathogens, commercial aspects
Poinar, G.O. & G.M. Thomas 1984. Laboratory Guide to Insect Pathogens adn Parasites. Plenum, New York.
Steinhaus, E.A. 1946. Insect Microbiology. Comstock Publ. Co., Ithaca.
Steinhaus, E.A. 1949. Principles of Insect Pathology. McGraw-Hill, New York
Steinhaus, E.A. 1963 ed. Insect Pathology, and Advanced Treatise. 2 Vols. Academic Press, New York.
M.V. Sternshis, 2004. Ecologically safe control of insect pest: the past, the present and the future. In: Emerging concepts in plant health management, R.T. Lartey & A. Caesar, eds. ISBN: 81-7736-227-5. Deals exclusively with microbials

Biological control of plant pathogens

Baker, K.F. & R.J.Cook, 1974. Biological Control of Plant Pathogens. Freeman, San Francisco: 433 pp.
Cook, R.J. & K.F. Baker, 1983. The nature and practice of biological control of plant pathogens. American Phytopathological Society, St. Paul: 539 pp. Extensive book on control of pathogens, update of the 1974 book by the same authors.
Campbell, R. 1989. Biological control of microbial plant pathogens. Cambridge University Press, Cambridge: 218 pp. Introduction to the subject for undergraduate students.
Hornby, D. ed. 1990. Biological control of Soil-Borne Plant Pathogens. CAB Intern. Press, Wallingford, Oxon: 479 pp.
Mukerji, K.G. & K.L. Garg eds. 1988. Biocontrol of plant diseases. CRC Press, Boca Raton, 2 Vols: 211 + 198 pp. Covers various aspects of the biological control of fungal diseases, nematoeds, insects and weeds.

Biological control of weeds

Coombs, Eric M., Janet K. Clark, Gary L. Piper, and Alfred F. Cofrancesco, Jr. (eds.). 2004. Biological Control of Invasive Plants in the United States. Oregon State University Press. 467 p.
Harley, K. L. S. and I. W. Forno. 1992. Biological Control of Weeds: a handbook for practitioners and students. Inkata Press, Melbourne. 74 p.

Huffaker, C. B. 1964. Fundamentals of biological weed control. In, P. DeBach (ed.), Biological Control of Insect Pests & Weeds. Chapman and Hall, London. pp. 631-649

Huffaker, C.B. 1959. Biological control of weeds with insects. Ann. Rev. Ent. 4: 251-276.

Jacob, H. S. and D. T. Briese. 2003. Improving the selection, testing and evaluation of weed biological control agents. Proceedings of the CRC for Australian Weed Management Biological Control of Weeds Symposium and Workshop, Sept. 13, 2002, University of Western Australia, Perth. CRC for Australian Weed Management Technical Series no. 7. 98 p.

Julien, M.H. ed. 1987. Biological control of weeds: a world catologue of agents and their target weeds. CAB International, Wallingford, Oxon: 150 pp. Reference catalogue containing comprehensive lists giving summarized information on natural enemies and weeds with literature references. It documents developments up to the end of 1985.

Julien, M.H., 1989. Biological control of weeds worldwide: trends, rates for success and the future. Biocontrol News and Information 10: 299-306.

Julien, M. and G. White, eds. 1997. Biological Control of Weeds: theory and practical application. ACIAR Monograph No. 49. 192 p.

Julien, M. and G. White. 1999. Biological Control of Weeds; A world catalogue of agents and their target weeds, fourth edition. CABI Publishing, Wallingford, UK. 223 p.

Nechols, J.R., L.A. Andres, J.W. Beardsley, R.D. Goeden and C.G. Jackson (editors), Biological Control in the Western United States: Accomplishments and benefits of regional research project W-84, 1964-1989. University of California, Division of Agriculture and Natural Resources, Oakland. Publ. 3361.

Olckers, T. and M. P. Hill. 1999. Biological control of weeds in South Africa (1990-1998). African Entomology Memoir No. 1. 182 p.

Rosenthal, S.S., D.M. Maddox & K. Brunetti 1985. Biological control methods. In: Principles of Weed Control in California. Thomson, Fresno: 65-94.

Wilson, F. 1964. The biological control of weeds. Ann. Rev. Ent. 9: 225-244.

Mass production, shipment and release of natural enemies

De Clercq, P. (2004). Culture of natural enemies on factitious foods and artificial diets. *In:* Encyclopedia of Entomology (J. L. Capinera, Ed.). Kluwer Academic Publishers, Dordrecht, vol. I, 650-652.

Lenteren, J.C. van, 1986. Evaluation, mass production, quality control and release of entomophagous insects. In: Biological Plant and Health Protection. ed.: J.M.Franz. Series Progress in Zoology 32. Fischer, Stuttgart: 31-56.

Lenteren, J.C. van & M.G. Tommasini, 2003. Mass Production, Storage, Shipment and Release of Natural Enemies. Chapter 12 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 181-189.

Quality control of natural enemies

Bueno, V.H.P. (Ed.), 2000. Controle Biológico de Pragas: Produção Massal e Controle de Qualidade. Editora UFLA, Lavras.

Lenteren, J.C. van (ed.), 2003. Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. CABI Publishing, Wallingford, UK: 327 pp.

Lenteren, J.C. van, 2003. Need of quality control of mass-produced biological control agents. Chapter 1 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 1-18.

Lenteren,J.C. van, A. Hale, J.N. Klapwijk, J. van Schelt and S. Steinberg, 2003. Guidelines for quality control of commercially produced natural enemies. Chapter 19 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 265-303.

Commercial aspects of biological control

Bolckmans, K.J.F., 1999. Commercial aspects of biological pest control. *In* “Integrated Pest and Disease Management in Greenhouse Crops” (R. Albajes, M.L. Gullino, J.C. van Lenteren and Y. Elad, Eds.), pp. 310-318. Kluwer Academic Publishers, Dordrecht.

Lenteren, J.C. van, M.M. Roskam & R. Timmer, 1997. Commercial mass production and pricing of organisms for biological control of pests in Europe. Biological Control 10: 143-149.

Lenteren, J.C. van, 2003. Commercial availability of biological control agents. Chapter 11 in: Quality Control and Production of Biological Control Agents: Theory and Testing Procedures. J.C. van Lenteren (ed.), CABI Publishing, Wallingford, UK: 167-179.

Evalation of efficiency of natural enemies

Pre-introduction evaluation

Ehler, L.E. 1990. Introduction strategies in biological control of insects. In M. Mackauer, L.E. Ehler, J. Roland eds. Critical Issues in Biological Control. Intercept, Andover: 111-134.

Gonzalez, D. & F.E. Gilstrap 1992. Foreing exploration: assessing and prioritizing natural enemies and consequences of preintroduction studies. (in press)

Lenteren, J.C. van, 1980. Evaluation of control capabilities of natural enemies: does art have to become science? Neth. J. Zool. 30: 369-381.

Lenteren, J.C. van & Manzaroli, G., 1999. Evaluation and use of predators and parasitoids for biological control of pests in greenhouses. In "Integrated Pest and Disease Management in Greenhouse Crops", R. Albajes, M.L. Gullino, J.C. van Lenteren & Y. Elad (eds.). Kluwer Publishers, Dordrecht: 183-201.

Waage, J.K. 1990. Biological theory and the selection of biological control agents. In M. Mackauer, L.E. Ehler, J. Roland eds. Critical Issues in Biological Control. Intercept, Andover: 135-157.

Post-introduction evaluation

Beirne, B.P. 1975. Biologcal control attempts by introductions against pest insects in the field in Canada. Canad. Entom. 107 (3): 225-236.

DeBach, P., & B.R. Bartlett, 1964. Methods of colonization, recovery and evaluation. In: DeBach, P. ed., 1964. Biological Control of Insect Pests and Weeds. Cambridge University Press, Cambridge: 402-426.

DeBach, P., & C.B. Huffaker, 1971. Experimental techniques for evaluation of the effectiveness of natural enemies. In: Huffaker, C.B., ed., 1971, Biological Control. Plenum, New York: 113-140.

DeBach, P., C.B. Huffaker & A.W. MacPhee, 1976. Evaluation of natural enemies. In: Huffaker, C.B. & P.S. Messenger, 1976. Theory and Practice of Biological Control. Academic Press, New York: 255-288.

Franz, J.M., 1973. Introductory review on the need for evaluation studies in relation to integrated control. J. Appl. Ecol. 10: 321-323.

Harris, P., 1973. The selection of effective agents for the biological ocntrol of weeds. Can. Entom. 105: 1495-1503.

Lenteren, J.C. van, 1980. Evaluation of control capabilities of natural enemies: does art have to become science? Netherlands Journal of Zoology 30: 369-381.

Lenteren, J.C. van, 1986. Evaluation, mass production, quality control and release of entomophagous insects. In: Biological Plant and Health Protection. ed.: J.M.Franz. Series Progress in Zoology 32. Fischer, Stuttgart: 31-56.

Luck, R.F. 1981. Parasitic insects introduced as biological agents for arthropod pests. CRC Handbook of Pest Management in Agric. 2: 125-284.

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Mackauer, M., & R. van den Bosch, 1973. General applicability of evaluation results. J. Appl. Ecol. 30: 330-335.

Zwoelfer, H., M.A. Ghani & V.P. Rao, 1976. Foreign exploration and importation of natural enemies. In: Huffaker, C.B. & P.S. Messenger, 1976. Theory and Practice of Biological Control. Academic Press, New York: 189-208.

Theoretical basis of biological control and modelling

Grasman, J., O.A. van Herwaarden, L. Hemerik & J.C. van Lenteren, 2001. A two-component model of host-parasitoid interactions: determination of the size of inundative releases of parasitoids in biological pest control. Mathematical Biosciences 169: 207-216.

Hawkins, B.A. & H.V. Cornell, 1999. Theoretical Approaches to Biological Control. Cambridge University Press: 412 pp.

Thompson, W.R. 1939. Biological control and the theories of interactions of populations. Parasitology 31: 299-388.

Origin of pests

Barbosa, P & J.C. Schultz ed. 1987. Insect Outbreaks. Academic Press, San Diego: 578 pp. Examples of outbreaks in natural and manipulated systems. Biotic and abiotic factors causing outbreak situations and evolutionary consequences.

Sailer, R., 1983. Exotic plant pests. In: Wilson, C.L. & Graham ** eds. 1983.
Wilson, C.L. & C.L. Graham eds. 1983. Exotic Plant Pests and North American Agriculture. Academic Press, New York: 522 pp. An impressive overview of origins of pests, diseases and weeds and measures to prevent further aggrevation.

Relationship between host-plant resistance and biological control

Boethel, D.J. & R.D. Eikenbary ed. 1986. Interactions of plant resistance and parasitoids and predators of insects. Ellis Horwood, Chicester: 224 pp. A number of articles describe positive and negative effects of host-plant resistance on biological control. Both chemical and morphological plant characteristics are considered.
Lenteren, J.C. van & O.M.B. de Ponti, 1990. Plant-leaf morphology, host-plant resistance and biological control. Proc. 7th Int. Symp. Insect-Plant Relationships. 3-8 June 1989, Budapest, Hungary; Akadémiai Kiadó, Budapest, Synp. Biol. Hung. 39: 365-386.

Relationship between biological and chemical control

van den Bosch, R. 1978. The Pesticide Conspiracy. Univ. of Calif. Press, Berkeley: 226 pp. Firework and very instructive for those naïve in the business of pest control. Helps you to become a bit more assertive when "selling" biological control.
Croft, B.A. 1990. Arthropod biological control agents and pesticides. Wiley, New York: 723 pp. Comprehensive text covering all aspects of biological control and the use of chemical pesticides, e.g. pesticide susceptibility of natural enemies, pesticide influences on natural enemies, pesticide selectivity, resistance to pesticides in natural enemies.
Information on negative effects of pesticides on natural enemies: *********

Literature on specific types of biological control

Biological control of aphids

Minks, A.K. & P. Harrewijn ed. 1988 & 1989. Aphids: their biology, natural enemies and control. Elsevier, Amsterdam, Vol 2 and 3: 364 & 312 pp. Volume 2 contains a lot of information on natural enemies of aphids, volume 3 has details on biologcal and integrated control in the field and greenhouses.
Niemczyk, E. & A.F.G. Dixon eds. 1988. Ecology and Effectiveness of Aphidophaga. SPB Academic Publishing, The Hague: 346 pp. Proceedings of a conference focussed on the effectiveness of natural enemies in limiting the abundance of aphids. The book demonstrates that biocontrol of aphids is apparently difficult to realise.

Biological control of citrus pests (scales and more)

Lenteren, J.C. van & P. DeBach, 1981. Host discrimination in three ectoparasites (*Aphytis coheni*, *A. lingnanensis* and *A. melinus*) of the oleander scale (*Aspidiotus nerii*). Netherlands Journal of Zoology 31: 504-532.
Lenteren, J.C. van, 1993. Oviposition behaviour of *Aphytis* (Hymenoptera, Chalcidoidea, Aphelinidae), parasitoids of armoured scale insects (Homoptera, Coccoidea, Diaspididae). In: "Biology of *Aphytis*" D. Rosen ed. Intercept, Andover: 13-39.
Smith, D., Beattie, G.A.C and Broadley, R. (eds) 1997. Citrus pests and their natural enemies. Department of Primary Industries, Brisbane, Australia. 272 pp.

Biological control and IPM of greenhouse pests

Albajes, R., Gullino, M.L., van Lenteren, J.C. & Elad, Y. (eds.), 1999. Integrated Pest and Disease Management in Greenhouse Crops. Kluwer Publishers, Dordrecht: 568 pp.
Hussey, N.W., & L. Bravenboer, 1971. Control of pests in glasshouse culture by the introduction of natural enemies. In: Huffaker, C.B., ed., 1971, Biological Control. Plenum, New York: 16-67.
Hussey, N.W., & N. Scopes, eds., 1886.
IOBC/WPRS, 1970, 1973, 1976, 1980, 1983, 1987, 1990, 1993, 1996, 1999, 2002, 2004, 2005. Proceedings of the working group "Integrated Control in Glasshouses".
Lenteren, J.C. van, P.M.J. Ramakers & J. Woets, 1980. Integrated control of vegetable pests in greenhouses. In: Integrated control of insect pests in the Netherlands, ed. A.K.Minks & P.Gruys. Pudoc, Wageningen: 109-118.
Lenteren, J.C. van, 1986. Parasitoids in the Greenhouse: successes with seasonal inoculative release systems. In: Insect parasitoids: J.K. Waage & D.J. Greathead, eds. Academic Press, London: 341-374.
Lenteren, J.C. van & J. Woets, 1988. Biological and Integrated Pest Control in Greenhouses. Annual Review of Entomology 33: 239-269.

Lenteren, J.C. van, M. Benuzzi, G. Nicoli & S. Maini 1992. Biological control in protected crops in Europe. In: "Biological Control and Integrated Crop Protection: towards environmentally safer agriculture" J.C. van Lenteren, A.K. Minks & O.M.B. de Ponti, eds. Pudoc, Wageningen: 77-89.

Lenteren, J.C. van, 1995. Integrated Pest Management in Protected Crops. In: Integrated Pest Management, D. Dent, ed. Chapman and Hall, London: 311-343.

Lenteren, J.C. van, Y.C. Drost, H.J.W. van Roermund & C.J.A.M. Posthuma-Doodeman, 1997. Aphelinid parasitoids as sustainable biological control agents in greenhouses. Journal of Applied Entomology 121: 473-458.

Lenteren, J.C. van, 2000. A greenhouse without pesticides: fact of fantasy? Crop Protection 19:375-384.

Parrella, M.P., L.Stengard Hansen & J.C. van Lenteren, 1999. Glasshouse environments. Glasshouse environments. In: Handbook of Biological Control. T.S. Bellows & T.W. Fisher, eds. Academic Press, San Diego: 819-839.

Biological control of lepidoptera with **Trichogramma** *and* **

Noldus, L.P.J.J., J.C. van Lenteren & W.J. Lewis, 1991. How *Trichogramma* parasitoids use moth sex pheromones as kairomones: orientation behaviour in a wind tunnel. Physiological Entomology 16: 313-327

Smith, S.M., 1996. Biological control with *Trichogramma*: advances, successes, and potential of their use. *Annu. Rev. Entomol.* 41, 375-406.

Biological control of mites

Helle, W. & M.W. Sabelis eds. 1985. Spider mites. Their biology, natural enemies and control. 2 Vols., Elsevier, Amsterdam: 405+458 pp. The first volume deals extensively about the pest organisms. The second volume is on natural enemies, damage caused by mites and control of mites. This volume provides a detailed account of the Phytoseiidae as predators on spider mites, with less detailed accounts of other predacious mites, spiders, and predacious insects and pathogens of spider mites.

Biological control of medical and veterinary pests

Chapman, H.C. ed. 1985. Biological control of Mosquitos. Bull. No.6, Amer. Mosq. Contr. Assoc. : 218 pp.

Biological control of muscoid flies

Patterson, R.S. & D.A. Rutz eds. 1986. Biological Control of Muscoid Flies. Misc. Publ. Ent. Soc. Amer. 62: 174 pp.

Biological control of nematodes

Jatala, P. 1985. Biological control of nematodes. In Advanced Treatise on Meloidogyne. Vol. 1: Biology and Control, J.N. Sasser & C.C. Carter. Dept. Plant Pathology, North Carolina State Univ., Raleigh: 303-308. Review of biological control of Meliodogyne spp.

Poinar, G.O. & H.B. Jansson eds. 1988. Diseases of Nematodes. CRC Press, Boca Raton, 2 Vols.: 149 + 150 pp. Both noninfectious and infectious diseases are treated comprehensively. Viruses, bacteria, protozoans, rickettsia, fungal parasites and predators of nematodes are listed and organisms which have the potential for the biological control of nematodes are discussed.

Biological control of thrips

Driesche, R.G. van, K.M. Heinz, J.C. van Lenteren, A. Loomans, R. Wick, T. Smith, P. Lopes, J.P. Sanderson, M. Daughtrey & M. Brownbridge, 1998. Western flower thrips in greenhouses: a review of its biological control and other methods. University of Massachusetts, Amherst, Massachusetts: 30 pp.

Lenteren, J.C. van and A.J.M. Loomans, 1998. Is there a natural enemy good enough for biological control of thrips? Proceedings 1998 Brighton Crop Protection Conference – Pests and Diseases 2, pp. 401-408, British Crop Protecton Council, Farnham, UK

Loomans, A.J.M, T. Murai, P.J.N.F. van Heest & J.C. van Lenteren, 1995. *Ceranisus menes* (Hymenoptera: Eulophidae) for control of Western Flower Thrips: biology and behavior. In: Thrips Biology and Management, B.L. Parker, M. Skinner & T. Lewis (Eds.), Plenum, New York: 263-268.

Loomans, A.J.M., J.C. van Lenteren, M.G. Tommasini, S. Maini & J. Riudavets, 1995. Biological control of thrips pests. Wageningen Agricultural Papers, 95 (1): 201 pp.

Parker, B.L., M. Skinner & T. Lewis (Eds.), 1995. Thrips Biology and Management. Plenum, New York.

Tommasini, M.G., J.C. van Lenteren, G. Burgio, 2004. Biological traits and predation capacity of four *Orius* species on two prey species. Bulletin of Insectology 57: 79-94.

Biological control of whiteflies

Burger, J.M.S., Gort, G., Lenteren, J.C. van and Vet, L.E.M., 2004. Natural history of whitefly in Costa Rica: an evolutionary starting point. Ecological Entomology 29: 150-163.

Drost, Y.C., J.C. van Lenteren & H.J.W. van Roermund, 1997. Life-history parameters of different biotypes of *Bemisia tabaci* (Hemiptera: Aleyrodidae) in relation to temperature and host plant: a selective review. Bulletin of Entomological Research 88: 219-229.

Drost, Y.C., Y.T. Qiu, C.J.A.M. Posthuma-Doodeman & J.C. van Lenteren, 2000. Comparison of searching strategies of five parasitoid species of *Bemisia argentifolii* Bellows & Perring (Homoptera: Aleyrodidae). Journal of Applied Entomology 124: 105-112.

Fransen, J.J. & J.C. van Lenteren, 1993. Host selection and survival of the parasitoid *Encarsia formosa* on greenhouse whitefly, *Trialeurodes vaporariorum*, in the presence of hosts infected with the fungus *Aschersonia aleyrodes*. The parasite-host relationship between *Encarsia formosa* (Hymenoptera: Aphelinidae) and *Trialeurodes vaporariorum* (Homoptera: Aleyrodidae). XL. Entomologia Experimentalis et Applicata 69: 239-249.

Fransen, J.J. & J.C. van Lenteren, 1994. Survival of the parasitoid *Encarsia formosa* after treatment of the parasitized greenhouse whitefly larvae with fungal spores of *Aschersonia aleyrodis*. Entomologia Experimentalis et Applicata 71: 235-243.

Gerling, D. (ed.) (1990) *Whiteflies: Their Bionomics, Pest Status and Management,* Intercept Ltd, Andover, Hants.

Gerling, D., and Mayer, R.T. (eds.) (1996) *Bemisia 1995: Taxonomy, Biology, Damage, Control and Management,* Intercept, Andover, Hants.

Henter, H.J., & J.C. van Lenteren, 1996. Variation between laboratory populations in the performance of the parasitoid *Encarsia formosa* on two host species, *Bemisia tabaci* and *Trialeurodes vaporariorum*. Entomologia Experimentalis et Applicata 80: 427-434.

Lenteren, J.C. van & L.P.J.J. Noldus, 1990. Whitefly-plant relationships: behavioural and ecological aspects. In: Whiteflies: Their Bionomics, Pest Status and Management, D. Gerling, ed. Intercept Ltd., Andover, Hants: 47-89.

Lenteren, J.C. van, Li Zhao Hua, J.W. Kamerman & R.M. Xu, 1995. The parasite-host relationship between *Encarsia formosa* (Hymenoptera: Aphelinidae) and *Trialeurodes vaporariorum* (Homoptera: Aleyrodidae). XXVI. Leaf hairs reduce the capacity of *Encarsia* to control greenhouse whitefly on cucumber. Journal of applied Entomology 119: 553-559.

Lenteren, J.C. van, H.J.W. van Roermund & S. Sütterlin, 1996. Biological control of greenhouse whitefly (*Trialeurodes vaporariorum*): how does it work? Biological Control 6: 1-10.

Lenteren, J.C. van & H.J.W. van Roermund, 1998. Why is the parasitoid *Encarsia formosa* so successful in controlling whiteflies? In "Theoretical Approaches to Biological Control", B.A. Hawkins & H.V. Cornell, eds. Cambridge University Press, Cambridge: 116-130.

Lenteren, J.C. van & Martin, N.A., 1999. Biological control of whitefly. In "Integrated Pest and Disease Management in Greenhouse Crops", R. Albajes, M.L. Gullino, J.C. van Lenteren & Y. Elad (eds.). Kluwer Publishers, Dordrecht: 202-216.

Lenteren, J.C. van & H.J.W. van Roermund, 1999. Why is the parasitoid *Encarsia formosa* so successful in controlling whiteflies? In "Theoretical Approaches to Biological Control", B.A. Hawkins & H.V. Cornell, eds. Cambridge University Press, Cambridge: 116-130.

Lenteren, J.C. van & Martin, N.A., 1999. Biological control of whitefly. In "Integrated Pest and Disease Management in Greenhouse Crops", R. Albajes, M.L. Gullino, J.C. van Lenteren & Y. Elad (eds.). Kluwer Publishers, Dordrecht: 202-216.

Manzano, M. R.; J. C. van Lenteren; C. Cardona & Y. C. Drost, 2000. Developmental time, sex ratio and longevity of *Amitus fuscipennis* MacGown and Nebeker (Hymenoptera: Platygastridae) on the greenhouse whitefly. Biological Control 18: 94-100.

Noldus, L.P.J.J. & J.C. van Lenteren, 1990. Host aggregation and parasitoid behaviour: biological control in a closed system. In : Critical Issues in Biological Control, M. Mackauer, L.E. Ehler & J. Roland, eds. Intercept Ltd, Andover, Hants: 229-262.

Roermund, H.J.W. & J.C. van Lenteren, 1992. The parasite-host relationship between *Encarsia formosa* (Hymenoptera: Aphelinidae) and *Trialeurodes vaporariorum* (Homoptera: Aleyrodidae). XXXIV. Life-history parameters of the greenhouse whitefly, *Trialeurodes vaporariorum* as a function of host plant and temperature. Wageningen Agricultural University Papers 92.3: 1-102.

Roermund, H.J.W. & J.C. van Lenteren, 1992. The parasite-host relationship between *Encarsia formosa* (Hymenoptera: Aphelinidae) and *Trialeurodes vaporariorum* (Homoptera: Aleyrodidae). XXXV. Life-history parameters of the greenhouse whitefly parasitoid *Encarsia formosa* as a function of host stage and temperature. Wageningen Agricultural University Papers 92.3: 103-147.

Roermund, H.J.W. van, J.C. van Lenteren & R. Rabbinge, 1997. Analysis of foraging behaviour of the whitefly parasitoid *Encarsia formosa* on tomato: an individual-based simulation approach. Biological Control 9: 25-47.

Qiu, Y.T., J.C. van Lenteren, Y.C. Drost & C.J.A.M. Posthuma-Doodeman, 2004. Life-history parameters of *Encarsia formosa, Eretmocerus eremicus* and *E. mundus*, aphelinid parasitoids of *Bemisia argentifolii* (Homoptera: Aleyrodidae). Eur. J. Entomol. 101: 83-94

Vet, L.E.M. & J.C. van Lenteren, 1981. The parasite-host relationship between *Encarsia formosa* (Hymenoptera: Aphelinidae) and *Trialeurodes vaporariorum* (Homoptera: Aleyrodidae). X. A comparison of three *Encarsia* spp. and one *Eretmocerus* sp. to estimate their potentialities in controlling whitefly on tomatoes in greenhouses with a low temperature regime. Journal of Applied Entomology 91: 327-348.

Vis, R.M.J. de, H. Mendez, J.C. van Lenteren, 2003. Comparison of foraging behavior, interspecific host discrimination, and competition of *Encarsia formosa* and *Amitus fuscipennis*. Journal of Insect Behavior 16: 117-152

Pest control including important sections on biological control

Hill, D.S., 1983. Agricultural Insect Pests of the Tropics and Their Control. Cambridge University Press, Cambridge: 746 pp.

Hill, D.S., 1987. Agricultural Insect Pests of Temperate Regions and Their Control. Cambridge University Press, London: 659 pp. A very broad book giving a survey of pests and methods of pest control, and describing all important pests species of temperate regions

Stoll, G., 2005. Natural crop protection in the tropics. Letting information come to life. Margraf Verlag. 2nd edition, 380 pp.; 15 ills. ISBN 3 8236 1317 0.

Risk assessment, host ranges, establishment, dispersal and non-target effects, exotics, invasions

Bigler F., Babendreier D., Kuhlmann U., eds., 2006. *Environmental Impact of Invertebrates in Biological Control of Arthropods: Methods and Risk Assessment*. Wallingford, UK: CAB Int. In press

Bigler F., Bale J. S., Cock M. J. W., Dreyer H., GreatRex R., Kuhlmann U., Loomans A.J.M. and Lenteren J.C. van, 2005. Guidelines on Information Requirements for Import and Release of Invertebrate Biological Control Agents (IBCAs) in European Countries. Biocontrol News and Information (in press).

Klinken, R.D., van, 2000. Host specificity testing: why do we do it and how can we do it better? In: Proceedings: Host Specificity of Exotic Arthropod Biological Control Agents: the Biological Basis for Improvement in Safety. R. van Driesche, T. Heard, A. McClay & R. Reardon, eds., pp. 54-68. Forest Service, Morgantown, USA.

Lenteren, J.C., van, 1997. Benefits and risks of introducing exotic macro-biological control agents into Europa. *Bull. OEPP/EPPO* 27, 15-27.

Lenteren, J.C. van, 1995. Frequency and consequences of insect invasions. In: Biological Control: Benefits and Risks. H.M.T. Hokkanen & J.M. Lynch, editors. Cambridge University Press, UK: 30-43.

Lenteren, J.C. van, Babendreier, D., Bigler, F., Burgio, G., Hokkanen, H.M.T., Kuske, S., Loomans, A.J.M., Menzler-Hokkanen, I., Rijn, P.C.J. van, Thomas, M.B., Tomassini, M.C., Zeng, Q.Q., 2003. Environmental risk assessment of exotic natural enemies used in inundative biological control. Biocontrol 48: 3-38.

Lenteren, J.C. van, Loomans, A.J.M., 2006. Environmental risk assessment: methods for comprehensive evaluation and quick scan. In:

Lenteren, J.C. van, Bale, J., Bigler, F, Hokkanen, H.M.T., Loomans, A.J.M., 2006. Assessing risks of releasing exotic biological control agents of arthropod pests. Annual Review of Entomology, 51 (in press).

Lenteren, J.C. van, Cock, M.J.W, Hoffmeister, T.S., Sands, D.P.A., 2006. Host specificity in arthropod biological control, methods for testing and interpretation of the data. In: Bigler F., Babendreier D., Kuhlmann U., eds. *Environmental Impact of Invertebrates in Biological Control of Arthropods: Methods and Risk Assessment*. Wallingford, UK: CAB Int. In press

Lynch, L.D., H. M. T. Hokkanen, D. Babendreier, F. Bigler, G. Burgio, Z.-H. Gao, S. Kuske, A. Loomans, I. Menzler-Hokkanen, M. B. Thomas, G. Tommasini, J. Waage, J. C. van Lenteren, Q.-Q. Zeng, 2000. Indirect effects in the biological control of arthropods with arthropods. In: Evaluating Indirect Ecological Effects of Biological Control, E. Wajnberg, J.C. Scott & P.C. Quimby (eds.). CABI publishing, Wallingford: 99-125

Van Drieiche, R.; Heard, T.; McClay, A.; Reardon, R. (tech. editors). 2000. Host-Specificity Testing of Exotic Arthropod Biological Control Agents: The Biological Basis for Improvement in Safety. July 8,1999, Bozeman, MT. Forest Health Technology Enterprise Team FHTET-99-1. Morgantown, WV. United States Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team. 95 p.

Van Driesche, R., S. Lyon, B. Blossey, M. Hoddle and R. Reardon (eds.). 2002. Biological control of Invasive Plants in the Eastern United States. USDA Forest Service Publication FHTET-2002-04. 413 p

Wilson, C.L. & C.L. Graham eds. 1983. Exotic Plant Pests and North American Agriculture. Academic Press, New York: 522 pp. An impressive overview of origins of pests, diseases and weeds and measures to prevent further aggrevation.

Withers, T. M., L. Barton-Browne & J. Stanley (eds.). 1999. Host specificity testing in Australasia: towards improved assays for biological control. Papers from the Workshop on Introduction of Exotic Biocontrol Agents -- Recommendations on Host Specificity Testing Procedures in Australasia, Brisbane, October 1998. Scientific Publishing, Indooroopilly, Queensland, Australia. 98 p

Integrated Pest Management

Albajes, R., Gullino, M.L., van Lenteren, J.C. & Elad, Y. (eds.), 1999. Integrated Pest and Disease Management in Greenhouse Crops. Kluwer Publishers, Dordrecht: 568 pp.

Delucchi, V, 1996. Integrated Pest Management: Quo Vadis? Parasitis 1986 Symposium Book, Geneve, Switzerland: 123-166.

Dent, D, 1995. Integrated Pest Management, Chapman and Hall, London: 356 pp.

Huffaker, C.B. ed. 1980. New Technology of Pest Control. Wiley, New York: 500 pp. This book presents a summary report of the progress towards integrated pest management systems within the framework of the NSF/EPA US National Integrated Pest Management Project. Interesting aspects on systems approach in IPM, relatively little practical results.

Lenteren, J.C. van & J. Woets, 1988. Biological and Integrated Pest Control in Greenhouses. Annual Review of Entomology 33: 239-269.

Lenteren, J.C. van, A.K. Minks & O.M.B. de Ponti, eds., 1992. Biological Control and Integrated Crop Protection: towards environmentally safer agriculture. Pudoc, Wageningen: 239 pp.Lenteren, J.C. van, 1993. Integrated pest management: the inescapable future. In "Modern crop protection: developments and perspectives", J.C. Zadoks ed. Wageningen Pers: 217-225.

Lenteren, J.C. van & W.A. Overholt, 1994. Ecology and Integrated Pest Management. Insect Science and Application 15: 557-582.

Lenteren, J.C. van, 1995. Integrated Pest Management in Protected Crops. In: Integrated Pest Management, D. Dent, ed. Chapman and Hall, London: 311-343.

Ruberson, J.R., ed., 1999. Handboook of Pest Management. Marcel Dekker, New York: 842 pp.

System approaches to pest production and pest management, including aspects of biocontrol

Boller, E.F., F. Haeni & H.M. Poehling (eds), 2004. Ecological infrastructures: Ideabook on Functional Biodiversity at the farm level. IOBC-WPRS Commission on Integrated Production Guidelines and Endorsement: 212 pp. ISBN 3-906776-07-7

Gurr, G.M., Wratten, S.D. and Altieri, M.A, 2004. Ecological Engineering for Pest Management. Advances in Habitat Manipulation for Arthropods. CSIRO Publishing, Melbourne.Lenteren, J.C. van, 1997. From *Homo economicus* to *Homo ecologicus*: towards environmentally safe pest control. In "Modern Agriculture and the Environment", D. Rosen, E. Tel-Or, Y. Hadar, Y. Chen (eds.), Kluwer Academic Publishers, Dordrecht: 17-31.

Lenteren, J.C. van, 2005. How can entomology contribute to sustainable crop protection? In: Heinz, Frisbie and Bogran (eds.), Crop Protection In A New Perspective.Texas A&M University (in press).Lewis, W.J., van Lenteren, J.C, Phatak, S.C. & Tumlinson, J.H. 1997. A total systems approach to sustainable pest management. Proc. Nat. Acad. Sci. USA 94, 12243-12248.

Lewis, W.J., J.C. van Lenteren, S.C. Phatak & J.H. Tumlinson, 1997. A total systems approach to sustainable pest management. Proceedings of the National Academy of Sciences, USA, 94: 12243-12248.

Children books on biological control

Quintana, P. & I. Massaguer, 2003. En vermelhó i en llargarut. Selmar, Barcelona (in Catalan)

Vandersteen, W., 1987. Suske en Wiske: de Woeste Wespen. Standaarduitgevery, Antwerpen, 54 pages (in Dutch).

Movies, videos and DVDs on biological control

20. Links to important websites

add www. before an address

International organizations with activities related to biological control or IPM activities

cgiar.org	CGIAR institutes
fao.org	FAO United Nations Food and Agricultural Organization
iaea.org	FAO IAEA International Atomic Engergy Agency
sibweb.org	Society for Invertebrate Pathology:

National organizations on biological control

seb.br	Brazil, see siconbiol
biocontrol.ca	Canada (biocontrol network canada)
centre-biological-control.dk	Denmark (Danish Center for Biological Control)
controlbiologico.org.mx	Mexico

International Symposia on biological control

International Symposia on Biological Control of Arthropods (ISBCA): website for next meeting to be constructed, for contacts: wrattens@lincoln.ac.nz
International Symposia on Biological Control of Weeds (ISBCW): website for next meeting to be constructed, for contacts: andy.sheppard@csiro-europe.org

Organizations dealing with guidelines regulations concerning import and release of natural enemies

aphisweb.aphis.usda.gov/ppq/permits/biological/index.html	USA Aphis
cnpma.embrapa.br/biocontrol/	Brazilian regulations import natural enemies
epa.qld.gov.au/	USA EPA
eppo.org/	EPPO (European Plant Protection Organization)
eppo.org/Standards/era_finalversions.html	EPPO pest risk analysis, white lists of natural enemies
fao.org	FAO
nappo.org	NAPPO (North American Plant Prot. Org.)
oecd.org/home/	OECD
who.int/whr/en/	WHO (World Health Organization, world health report)

Information on biological control and IPM

faculty.ucr.edu/~legneref	Dr. Fred Legner's biological control encyclopedia
ipmeurope.org/About%20IPME/Background.htm	
ipm.ucdavis.edu	
ipmworld.umn.edu/textbook.htm	textbook on IPM
nysaes.cornell.edu/ent/biocontrol/	
pestinfo.org	data base scientists biological control and IPM

Information on biodiversity

biodiversitysummit.nl/en-index.html	Biodiversity summit 2002

Information on insects, general, natural enemies and pests

aphisweb.aphis.usda.gov/ppq/permits/biological/index.html	
bba.de/eggpara/eggp.htm	egg parasitoids newsletter; *Trichogramma* etc.
cnia.inta.gov.ar/trichogramma	bulletin on *Trichogramma*
ent.iastate.edu/List/	
IFAS.UFL.EDU/~ent2/wfly/index.html	whiteflies
insectweb.inhs.uiuc.edu/soy/siric	insects in soy
pest.cabweb.org	
pestinfo.org	pests and natural enemies

Information on invasive species

http://www.cabi-bioscience.ch/wwwgisp/gtcsum.htm
eppo.org/QUARANTINE/Diabrotica_virgifera/diabrotica_virgifera.html#map-dia)
issg.org/
http://www.issg.org/features/pestcontrol.html

Agro-ecology, functional biodiversity and landscape ecological approaches

cast-science.org/pdf/biod.pdf	
nature.berkeley.edu/~agroeco3/index.html	agro-ecology in action
iobc.ch/org.list.html	IOBC integrated production guidelines

Producers of natural enemies (selection)

amwnuetzlinge.de	Germany
anbp.org	USA (Association of Natural Biocontrol Producers)
appliedbionomics.com	UK
arbico.com	USA
avancebiotechnologies.com	Chile
bio-bee.com	Israel
biobest.be	Belgium
biocont.cz	Czech Republic (Biocont Laboratory)
biocontrol.ch	Switzerland (Andermatt Biocontrol)
biocontrole.com.br	Brazil
biological-crop-protection.co.uk	UK
bionativa.cl	Chile
bioplanet.it	Italy
bioplant.dk	Denmark (Borregaard Bioplant)
biorend bioagro	Chile
biotop.fr	France
certiseurope.co.uk	UK (Biological Crop Protection / Certis)
bugsforbugs.com.au	Australia
bug@islandnet.com	Canada (Applied Bionomics)
controlbiologico.cl	Chile
degroenevlieg.nl/home.html	The Netherlands
e-nema.de	Germany
entocare.nl	The Netherlands
ibma.ch	Internation Biocontrol Manufacturers Association
insectary.com	Canada (Beneficial Insectary)
intrachem.com	Italy
ipmlabs.om	USA (IPM Laboratories)
koppert.com	The Netherlands
kunafin.com	USA (Trichogramma insectories)
landireba.ch	Switzerland
mip-agro controladores biologicas	Chile
natural-insect-control.com	Canada
naturescontrol.com	USA
neudorff.de	Germany
nuetzlinge.de	Germany (Sautter & Stepper)
nuetzlingeanbieter.de	overview of natural enemies / companies in Germany
nijhofbgb.nl	The Netherlands, Nijhof Biologische Gewasbescherming
syngenta-bioline.co.uk	UK
thebugfactory.ca	Canada
rinconvitova.com	USA
wyebugs.co.uk	UK
xilema (axilema@yahoo.com)	Chile
mmzapater@arnet.com.ar	Argentina

Resistance of insects against pesticides

cips.msu.edu/whalonlab/rpmnews/

Taxonomy of arthropods, scientific and popular names of arthropods

animaldiversity.ummz.umich.edu/arthropoda/insecta.html
ent.iastate.edu/List/cd-rom.html entomology index
na.fs.fed.us/spfo/pubs/silvics_manual/Volume_1/checklist_of/insects_and_mites.htm scientif and popular names of insects
tolweb.org/tree?group=Endopterygota&contgroup=Neoptera#about tree of life project

Journals publishing articles on biological control

Biocontrol (Official Journal of IOBC)	springeronline.com/sgw/cda/frontpage/0,11855,5-40109-70-35621340-0,00.html
Biological Control	elsevier.com/locate/issn/1049-9644
Bulletin of Insectology	
Entomologia Experimentalis et Applicata	blackwellpublishing.com/journal.asp?ref=0013-8703
European Journal of Entomology	eje.cz
Journal of Insect Behaviour	
Neotropical Entomology	seb.org.br/bioassay

Entomological meetings / conferences

ice2008.org.za	int congress entomology, Durban, South Africa 2008
ipmnet.org	meeting agenda IPM and biological control
sciref.org/links/EntEvent/index.htm	international meeting agenda
ufrpe.br/xxicbe	21st Brazilian congress of Entomology

Entomological societies

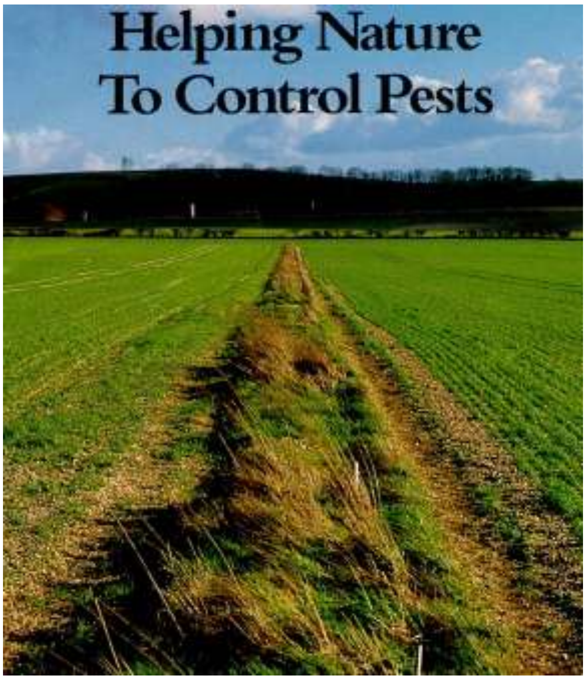
sciref.org/links/EntSco/intro.htm international listing of entomological societies

Biological control societies

www.controlbiologico.org.mx listing of Mexican biocontrol workers

Plants of economic importance

faculty.ucr.edu/~legneref/botany/index.html



Acknowledgements

All those who contributed with text and data are gratefully acknowledged. Marianne Bergeman is thanked for her assistance in preparing this internet book. The following persons contributed material for this book: Karel Bolckmans (The Netherlands), Ernst Boller (Switzerland), Vanda Bueno (Brazil), Patrick DeClercq (Belgium), Lisa Forster (USA), Marcus Gerding (Chile), David Greathead (UK), Simon Grenier (France), Yoshimi Hirose (Japan), Neil J. Holiday (Canada), Rami Kfir (South Africa), Fred Legner (USA), Robert Luck (USA), Roberto Parra (Brazil), Willem Ravensberg (The Netherlands), Jean-Louis Schwartz (Canada), Lincoln Smith (USA), Margarita Shtenshis (Russia), Eizi Yano (Japan), and many more!

IOBC Global, Wageningen University and the Foundation for Integrated Farming supported the collection of material.

J.C. van Lenteren, February 2012, Wageningen, The Netherlands

Appendix 1. An overview of national and regional biological control books

This overview is far from complete. Please send us titles, a short summary and a jpeg picture of the front page of books in your language

International Organization for Biological Control of Noxious Animals and Plants: History of the first 50 Years (1956-2006). Boller, E.F, J.C. van Lenteren and V. Delucchi (Eds.) 2006. IOBC, Zürich, 287 pp. The IOBC promotes the development of biological control and its application in integrated plant protection and production programmes. IOBC coordinates biological control activities worldwide in six Regional Sections and in Working Groups. This book describes the origin and development of the organization, and summarizes its current actvities. The book can be ordered at Joop.vanLenteren@wur.nl (10 Euro / 15 US$ including shipment)

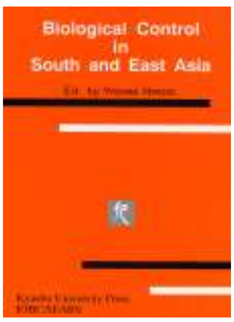
Africa

Neuenschwander, P, C. Borgemeister and J. Langewald, (eds.) 2003. Biological Control in IPM Systems in Africa. CABI Publishing, Wallingford, UK, 414 pp.
A recent overview of all African biological control projects

Argentina

Lecuona ,R.E. (ed.), 2004. Bioinsumos: Una Contribucion a la Agricultura Sustentable. Ediciones Instituto Nacional de Technologia Agropecuaria, 58 pp. Booklet providing information about all categories of natural enemies (predators, parasitoids and pathogens), antagonists of diseases and composting; with illustrations. In Spanish.

Molinari, A.M., 2005. Control Biologico: Espescies entomofagas en cultivos agricolas. Ediciones Instituto Nacional de Technologia Agropecuaria, 80 pp. Nicely illustrated booklet giving an overview on beneficial organisms (predators, parasitoids and pathogens). Surprisingly with advertisments of chemical control companies. In Spanish.



Asia

Biological Control in South and East Asia. Y. Hirose (Ed.)., Kyushu University Press, Kyushu, 1992, 68 pp. Overview of biological control activities in China, India, Japan, Malaysia, Philippines and Thailand in the 1990s.

Austria
Nützlinge- Helfer im zeitgemässen Pflanzenschutz", Blümel, S.; Fischer-Colbrie,P & E.Höbaus, 1998 Verlag Jugend&Volk, Wien.pp. 143. New edition to appear in May 2006, same title, same authors.

Australia
Broadley, R. & M. Thomas, 1995. The good bug book: beneficial insects and mites available in Australia for biological pest control. Australian Biological Control Inc., Richmond,53 pp.
Waterhouse, D.F. & D.P.A. Sands, ****. Classical biological control of arthropods in Australia. ACIAR Monograph 77.
Waterhouse, D.F. and Norris, K.R. (1987) *Biological control: Pacific prospects*. Inkata Press, Melbourne, Australia.
Waterhouse, D.F. and Sands, D.P.A. (2001) *Classical biological control of arthropods in Australia*. ACIAR Monograph No. 77, Australian Centre for International Agricultural Research, Canberra, Australia.
Waterhouse, D.F. (1998a) *Biological control of insect pests: Southeast Asian prospects.* ACIAR Monograph No 51. Australian Centre for International Agricultural Research, Canberra, Australia.

Belgium
Vandersteen, W., 1987. Suske en Wiske: de Woeste Wespen. Standaarduitgevery, Antwerpen, 54 pages (in Dutch).

Sterk, G., 1991. De geïntegreerde bestrijding in de fruitteelt. IWONL. Opbouwwerk Interleuven. OVG, 225 pp.

Brazil
Bueno, V.H.P. (Ed.), 2000. Controle Biológico de Pragas: Produção Massal e Controle de Qualidade. Editora UFLA, Lavras.

Parra, J.R.P., P.S.M.Botelho, B.S.Corrêa-Ferreira and J.M.S.Bento (eds.) 2002.Controle Biológico no Brasil. Parasitóides e Predadores. Ed. Manole,Sao Paolo, 635p.

Canada
Vincent, Ch. & Coderre, D. (ed.), 1992 . La lutte biologique. Lavoisier, 702 pp. L'ouvrage regroupe les contributions de 37 spécialistes canadiens. Les intitulés des chapitre sont : Introduction ; Lutte contre les insectes nuisibles ; Utilisation des prédateurs ; Utilisation des parasites; Lutte contre les mauvaises herbes ; Résistance des plantes et méthodes culturales;

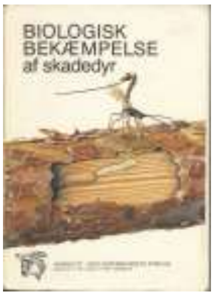
Phytopathologie ; Lutte biologique et vertébrés ; Lutte biologique et composés chimiques ; Conclusion.

Chile

Rojas, S., 2005. Biological Pest Control in Chile: History and Future. Libros INIA 12, Ministry of Agriculture, Instituto de Investigaciones Agropecuarias, 125 pp. ISBN 956-7016-19-4l ; ISSN 0717-4713. (In Spanish). This very well composed book was written by one of the senior researchers of biological control in Chile, Dr. Sergio Rojas P, and contains many beautiful colour illustrations of insects made by Dr. Renato Ripa S.

Colombia

Guia de insumos biologicos para el manego integrado de plagas. Corporacion para el Desarrolo de insumos y Servicios Agroelogicas Harmonia (only available in Spanish). Gives information about pests and natural enemies commercially available in Colombia.

Denmark

Borregaard, S., 1998**.** Sund have - på naturlig vis. Aschehoug forlag.
En omfattende håndbog for alle haveejere. I bogens første del finder man sygdoms-symptomerne beskrevet, og i anden del de forskellige nyttedyr og midler, der kan genoprette balancen. I bogen finder man tillige angivelser af de forskellige skadedyrs livscyklusser (på hvilken tid af året de lægger æg, bliver til larver, forpuppes og bliver voksne individer). Bogen er rigt illustreret med over 100 farvebilleder.

Eilenberg, J.; Philipsen, H.; Steenberg, T.; Øgaard, L. 1992. Mikrobiologisk Insektbekæmpelse [Microbial control of insect pests]. Teknologinævnet, Copenhagen, 55 pp. The book is a part of a series produced by the Danish board of Technology with the purpose to stimulate a public discussion on biotechnology. In this book the authors describe, what is microbial control of insects and which methods are needed for the development and implementation. The emphasis is on biotechnology, for example mass production and genetic manipulation.

Hansen, L. Stengård, O.C. Pedersen & J. Reitzel (1983): Skadedyr og nyttedyr - håndbog om biologisk bekæmpelse i drivhuset ("Pests and beneficials - handbook on biological control in glasshouses" in Danish). De Danske Haveselskaber. Copenhagen, Denmark. 110 pp. The book is directed at hobby-growers and deals with practical application of biological control in small glasshouses. Initial chapters describe insect biology and population development, principles of pest control, and the philosophy behind biological control.

Then practical application of beneficials against spidermites, whiteflies and aphids is descibed in detail. The final chapters illustrate other pests and benefcials to be found in glasshouses and as well as information on the potential of biological control in other sectors, e.g. field crops and forestry. An appendix describes how the grower can propagate his own beneficials and maintain a colony over winter. The book is richly illustrated.

Holm, E. (ed.) 1977. Biologisk bekæmpelse af skadedyr [Biological control of insect pests]. Kaskelot, Gedved, 144 pp. The book was the first in Danish to compile information about biological control of pest insects. The main emphasis is thus on Danish conditions. Scientists involved in biological control wrote chapters dealing with specific topics, for example integrated control, microbial control, predators and parasitoids. Further, the book contains information about other methods, which are relevant for biological control, for example attractants, hormones and physical control

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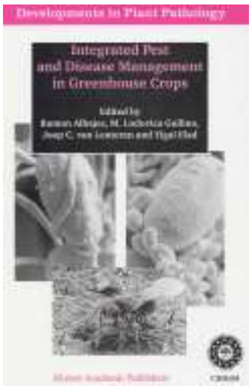


Europe

Albajes, R., Gullino, M.L., van Lenteren, J.C. & Elad, Y. (eds.), 1999. Integrated Pest and Disease Management in Greenhouse Crops. Kluwer Publishers, Dordrecht: 568 pp.

Lenteren, J.C. van, A.K. Minks & O.M.B. de Ponti, eds., 1992. Biological Control and Integrated Crop Protection: towards environmentally safer agriculture. Pudoc, Wageningen: 239 pp.

Finland

Koskula, H., 2000. Kasvihuoneviljelmien tuhoeläimet ja niiden biologinen torjunta ("Pests in greenhouse crops and their biological control"). Kasvinsuojeluseura ry, 104 pp. The book gives the basic biology of different pests and their natural enemy. It has about 10 drawings, for example about differences between different aphid- and whitefly species and around 90 color pictures about the pests and their natural enemy.

France

Balachowsky, A.S., 1951 La lutte contre les insectes: principes, methodes, applications. Payot, Paris: 380 pp. IPM book with a large section on biological control.

Regnault-Roger, C., 2005. Enjeux phytosanitaires pour l'agriculture et l'environnement pesticides et biopesticides, agriculture durable, OGM, lutte intégrée et biologique. Lavoisier, ISBN 2-7430-0785-0

See also Canada

Germany

Fortmann, M., 1993. Das grosse Kosmosbuch der Nützlinge. Neue Wege der biologischen Schädlingsbekämpfung. Franckh-Kosmos, 320 pp. ISBN 3-440-06588-X.

Hassan, S.A., R. Albert & W.M. Rost, 1993. Pflanzenschutz mit Nützlingen. – im Freiland und unter Glas. 1993. 192 S., 43 Farbf., 50 sw-Fotos, 22 Tab., geb. ISBN 3-8001-5138-3.

Krieg, A. & J.M. Franz, 1989. Biologische Schaedlingsbekaempfung. Parey, Hamburg: 302 pp. The best German textbook on biological control, but only available second hand

Pschorn-Walcher, H. & Heitland, W, 2002. Parasitoide Online: Eine Einführung in die Welt der Parasitoide. http://www.faunistik.net/PONLINE/ponline.html (last accessed at 31 January 2006)

Schmutterer, H. & J. Huber, 2005. Natürliche Schädlingsbekämpfungsmittel. Ulmer Verlag, Stuttgart, 2005; 263 Seiten. ISBN 3-8001-4147-7. In 10 Kapiteln werden die Eigenschaften und die praktische Anwendung sämtlicher, in Deutschland und anderen europäischen Ländern verfügbarer, natürlicher Schädlingsbekämpfungsmittel übersichtlich dargestellt. Besonders eingegangen wird auf Herkunft, Gewinnung und Lagerfähigkeit, Wirkungsweise, chemische Struktur, Anwendung und Zielorganismen, Kombination mit anderen Bekämpfungsverfahren, Warmblütertoxizität, Phytotoxozität, Verhalten in der Umwelt, Nebenwirkungen und Resistenz.

Hungary

Balazs, K., Meszaros, Z., 1989. Biological control using natural enemies, Mezogazdasagi Kiado, Budpest, 210 pp. Richly illustrated basic book.

Italy

Biological and Integrated Control for Protected Cultivation (Lotta Biologica e Integrata nelle Colture Protette). M. Benuzzi & G. Nicoli. Biolab, Cesena, 1988, 167 pp. (only available in Italian). Well illustrated book about biological and integrated control in greenhouses. Pests and their natural enemies for a variety of greenhouse crops are described.

Benuzzi, M, Vacante, V., 2004. Difesa fitosanitaria in agricoltura biologica. Edagricole, Bologna, 297 pp. This book is about crop protection in biological agriculture. First, the technical methods and crop protection products available for biological production are summarized (natural enemeis, microbial products, plant produced pesticides, pheromones, other chemical products). Next, pest and disease management methods for all major Italian crops are discussed (e.g. apple, pear, peach, grape, vegetables, olive, potatoes, strawberries).

The Insect Factory (La Fabbrica degli Insetti). G. Celli, S. Maini & G. Nicoli. Franco Muzzio, Padova, 1991, 208 pp. (only available in Italian). One of the early books on "industrial" mass production of natural enemies; includes a number of mass rearing schemes and much practical information on rearing of natural enemies and their hosts.

Microbial Control of Herbivores (Lotta Microbiologica Contro i Fitofagi). K.V. Deseö Kovács & L. Rovesti. Edagricole, Bologna, 1992, 296 pp. (only available in Italian). A very thorough treatment, both practically and theoretically, of microbial control agents including nematodes. Deserves to be translated in English.

Biological Control (Lotta Biologica). M. Ferrari, E. Marzon, A. Menta, Edagricole, Bologna, 2000, 355 pp. (4th Edition, only available in Italian). General introduction to biological control and IPM, includes biological control.

Biological and Integrated Control (Lotta Biologica e Integrata). E. Viggiani, Liguori Editore, Napels, 1994, 517 pp. (only available in Italian). The first and largest part concerns a systematic overview of arthropod natural enemies. An introduction to biological control is given in the second part.

Mexico

Badii, M.H., A.E. Flores & L.J. Glan Wong (eds.) 2000. Fundamentos y Perspectivas de Control Biologico. Universidad Autonom de Nuevo Leon, Mexico, 462 pages ISBN: 970-694-033-2

A very complete book of biological control in Spanish. The 34 chapters cover the basis scientifical aspects of biocontrol (ecology, taxonomy) as well as applied aspects and case studies.

Latin America

Coulson J.R. & Zapater M.C. (editors) 1992. Opportunities for Implementation of Biocontrol in Latin America. IOBC-Global & IOBC-SRNT, Buenos Aires, 71 pages.

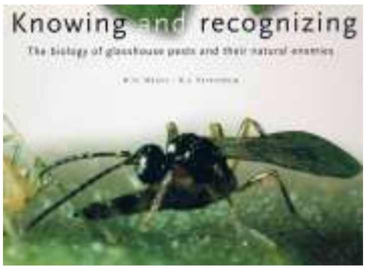
Zapater M.C. (editor) 1996. *El control biológico en América Latina*. IOBC-SRNT, Buenos Aires, 142 pages. In Spanish

The Netherlands

Anonymous, 1969. Leven met insekten: het onderzoek naar een geintegreerde bestrijding van plagen. Pudoc, Wageningen, 177 pp. Overview of the first ten years of research on biological control and integrated pest management of the Working Party on Integrated Control of Pests. (only available in Dutch)

Anonymous, 1980. Landbouw zonder spuit: geïntegreerde bestrijding van insektenplagen in de landbouw. Pudoc, Wageningen, 54. A richly illustrated book for layman explaining biological control and IPM. Overview of the first twenty years of research on biological control and integrated pest management of the Working Party on Integrated Control of Pests. (only available in Dutch)

Klomp, H. & Wiebes, J.T. (eds.) 1979. Sluipwespen in relatie tot hun gastheren. Pudoc, Wageningen, 198 pp. Overview of research on parasitoids in The Netherlands, including a chapter on biological control of pests with parasitoids. (only available in Dutch)



Malais, M.H. & W.J. Ravensberg, 2002. Kennen en herkennne: levenswijzen van kasplagen en hun natuurlijke vijanden. Reed Business Information, Doetinchem, 288 pp. Also available in English

Minks, A.K. & Gruys, P. (eds) 1980. Integrated control of insect pests in The Netherlands. Pudoc, Wageningen, 304 pp. Over view of all the research projects of the first twenty years of research on biological control and integrated pest management of the Working Party on Integrated Control of Pests. (only available in English)

Norway

There is no specific book on biological control in Norwegian. There are two Norwegian books on IPM with sections on biological control.

Heggen, H.E., Hofsvang, T. & Orpen, H.M., 2003. Plantevern i veksthus: Integrert bekjempelse, Tomat, Agurk. Landbruksforlaget, Oslo, 70 pp. http://www.bioforsk.no/dok/senter/phelse/aas/ipv/grs_vh.pdf

Heggen, H.E. & Toppe, B., 2003. Plantevern i veksthus: prydplanter: Integrert bekjempelse. Landbruksforlaget, Oslo, 163 pp. http://www.bioforsk.no/dok/senter/phelse/aas/ipv/prydpl_vh.pdf

Portugal

Amaro, P., 2003. A protecção integrada. Istituto Superior de Agronomia, Univ. Técnica de Lisboa, 446 pp. ISBN 972-8669-10-10. large section on biocontrol

see also Brazil

Russia

Pristavko, V.P. (ed.) 1975. Insect behavior as a basis for developing control measures against pests of field crops and forests. Naukova Dumka Publishers, Kiev, 238 pp. (Original version in Russian, translated in 1981 by USDA, Washington)

Shternshis M.V., F.S. Djalilov, I.V. Andreeva & O.G. Tomilova. Biologicheskaya zashchita rastenii (Biological plant protection) (Ed. M.V. Shternshis). 2004. Koloss, Moscow: 264 pp. (In Russian). This Russian textbook contains information on general and special aspects of biological control of plant pests. It starts with a background of biological control based on natural interaction of organisms and with main strategies of biocontrol. Next are the chapters on the description of beneficial insects and mites and their use in biocontrol. This is followed by chapters on insect pathogens and related formulations developed mainly in Russia. Then the similar information is presented on biological control of plant disease and weeds. The release of sterilized insects and application of some preparations based on natural biologically active compounds are also described. The last chapter is devoted to the examples of biological protection of some crops. The textbook is illustrated and supplied with the glossary of terms in biological control.

Shumakov, E.M., Gusev, G.V. & Fedorinchik, N.S. (eds.) 1974. Biological agents for plant protection. Moscow, Kolos, 490 pp. (Original version in Russian, translated in 1974 by USDA, Washington). This book was written by scientists of the USSR and other members of the SEV (Council of Economic Mutual Assistance), devoted to biological agents for plant protection. In it are presented the results of works on the utiliations of entomophages, pathogenic agents, and phytophages in combatting insect pests, diseases, and weeds of agricultural crops. The effectiveness of individual biological agents in the control of harmful organisms is shown. Principal attention is given to the practical use of entomophages and biopreparations and to the integrated method of plant protection. IPM is extensively addressed in this book.

Spain

Jacas, J., P. P. Caballero & J. Avilla (Eds.). 2005. El control biológico de plagas, enfermedades y malas hierbas y la sostenibilidad de la agricultura mediterránea. Publicacions de la Universitat Jaume I. Castelló de la Plana, 223 pp. (In Spanish). This book provides a wide overview of biological control. It starts with an introduction of the principles of biological control. Next biological control of pests and diseases is discussed. This is followed by chapters on biological control of pests and diseases in citrus and greenhouses, and of post-harvest pests and diseases. The book finishes with a chapter on the future of biological control. Much information about microbial control is presented.

Quintana, P. & I. Massaguer, 2003. En vermelhó i en llargarut. Selmar, Barcelona (in Catalan)
How to find natural enemies is explained in this book for children.

Sweden

Sandskär, B. (translator) 1999. Biologisk bekämpning av skadedjur. Jordbruksverket. ISBN-91 88 264-22-X, 72 pp
This biological control book in Swedish is a translation of the German "Biologische Schädlingsbekämpfung - Arbeitshilfe fur Beratung und Betriebsfuhrung" Stuttgart. It contains information about greenhouse pests and natural enemies and recommendations for IPM in selected crops

Switzerland

Boller, E., Häni, F. & Poehling, H.-M., 2004. Ecological Infrastructures: Ideabook on Functional Biodiversity at the Farm Level. ISBN 3-906776-07-7. 230 pp. EURO 25.-. Can be ordered at www.iobc.ch

Multifunctional agriculture, functional biodiversity, conservation biological control and ecological infrastructure are recent terms reflecting a change to a new philosophy in agricultural production. The IOBC Commission on Integrated Production Guidelines and Endorsement prepared this practical ideabook. Under the guidance of Dr. Ernst Boller, this Ideabook that contains a wealth of until now unavailable information, and may fill important gaps in common knowledge about Integrated Production. With tools like provided in this ideabook, IOBC pursues as international scientific organisation the traditional objective to make new, field-tested and sustainable knowledge available to the farmers' community.

Uruguay

Basso C. & Ribeiro A. (ed.) 2002. Enemigos naturales como reguladores de poblaciones de insecto: biodiversidad, conservación y manejo. Facultad de Agronomía, Montevideo. 182 p. Este libro contiene las conferencias dictadas en el marco del curso de posgrado: *"Enemigos naturales como reguladores de poblaciones de insectos: biodiversidad, conservación y manejo"* desarrollado en la Facultad de Agronomía de la Universidad de la República de Uruguay, 2001. Los autores de las conferencias incluyen especialistas de Francia (B. Pintureau y D. Rousse), de Argentina (E. Botto) y de Uruguay (C. Basso, J. Franco y G. Grille).

Basso C. & Grille G. 2001. Tecnología de producción masiva y liberación de *Trichogramma* (Hymenoptera, Trichogrammatidae) en los cultivos. Universidad de la República (Facultad de Agronomía) - Galosol SA. Montevideo. 36 p. En este libro incluye una breve presentación de la historia y realidad de la utilización de los parasitoides oófagos *Trichogramma* (Hymenoptera, Trichogrammatidae) en el mundo, y se describe la metodología de su producción en Uruguay, a partir de su hospedero alternativo *Ephestia kuehniella* Zeller (Lepidoptera, Pyralidae). Se mencionan las principales experiencias de utilización en este país, y los diferentes dispositivos de liberación empleados.

Appendix 2. Glossary

The glossary is based on various sources, like Bigler et al. (2006), Eilenberg et al. (2001), EFSA (2008, in preparation), FAO (2001), van Lenteren (2000), OECD (2004)

Assessment: A process of identifying, analysing and evaluating risks, costs or benefits associated with the introduction of a biological control agent

Antagonist: An organism (usually pathogen) which does no significant damage to the host but its colonisation of the host protects the host from significant subsequent damage by a pest.

Augmentative releases: Either inundative or seasonal inoculative releases, i.e. those forms of biological control where mass-produced, biological control agents are released to reduce a pest population without necessarily leading to continuing impact or establishment.

Beneficial organism: Any organism directly or indirectly advantageous to plants or plant products, including biological control agents

Benefit (in risk-benefit assessment): The value of a particular positive effect expressed in monetary or non-monetary terms

Biological control: Using biota to reduce biota (International Biological Program).

Biological control: The use of an organism to reduce the population density of another organism.

Biological control: Pest management strategy making use of living natural enemies, antagonists or competitors and other self-replicating biotic entities.

Biological control: there are about 30 definitions of biological control; the most important element of a biological control definition should be that a living organism is reducing the population density of another living organism

Biological control agent: A natural enemy, antagonist or competitor, and other self-replicating biotic entity used for pest management.

Biological pesticide (biopesticide): A generic term, not specifically definable, but generally applied to a microbial control agent, usually a pathogen, formulated and applied in a manner similar to a chemical pesticide, and normally used for the rapid reduction of a pest population for short-term pest management.

Classical biological control: The intentional introduction and permanent establishment of an exotic biological agent for long-term pest management.

Clearance of a consignment: Verification of compliance with phytosanitary regulations.

Commensalism: An association between two organisms of different species in which one derives some benefit while the other is unaffected.

Competitor: An organism which competes with pests for essential resources (e.g. food, shelter) in the environment.

Consignment: A quantity of plants, plant products and/or other regulated articles being moved from one country to another and covered by a single phytosanitary certificate.

Contaminants (for the introduction of invertebrate biological control agents): Inclusion of any unwanted organisms or substances in the commerce of natural enemies that poses a risk to the health of natural enemies, humans and/or to ecosystems

Cost (in risk assessment): The value of a particular adverse effect expressed in monetary or non-monetary terms

Direct effect (from the introduction of an exotic biocontrol agent): This involves physical interaction between the biocontrol agent and target or non-target organisms (effects can be positive, negative or neutral).

Ecological host range: The range of species a natural enemy parasitizes/feeds on/infects in nature (but see ‘physiological (= fundamental) host range’)

Ecoregion (also addressed as ecoarea): An area with similar fauna, flora and climate and hence similar concerns about the introduction of biological control agents
Ecosystem: A complex of organisms and their environment, interacting as a defined ecological unit (natural or modified by human activity, e.g. agroecosystem), irrespective of political boundaries.
Efficacy (of a biological control agent): The ability to cause a statistically significant reduction with regard to the number of pest organisms, direct and indirect crop damage, or yield loss.
Entomophagous: Organisms that eat insects
Entry (of a pest): Movement of a pest into an area where it is not yet present, or present but not widely distributed and being officially controlled
Environmental risk assessment: The process that analyses the likelihood of occurrence and magnitude of consequences of an adverse environmental effect
Eradication: Application of phytosanitary measures to eliminate a pest from an area.
Established species: Successful long-term survival and reproduction of a species after introduction into a new area.
Establishment (of a biological control agent): The perpetuation, for the foreseeable future, of a biological control agent within an area after entry.
Exotic: Not native to a particular country, ecosystem or ecoregion (-area).
Fundamental host range: see ‘physiological host range’
Generalist: See ‘host specificity’.
Harmful organism: Any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products (definition of EC Council Directive 2000/29/EC of 8 May 2000)
Hazard of adverse effects (from the release of biocontrol agents): Any imaginable adverse effect which can be named and measured (e.g. in biological control: direct and indirect adverse effects on non-target organisms and ecosystem).
Host range: Set of species that allow survival and reproduction of a natural enemy (see also ‘physiological (= fundamental) host range’ or ‘ecological host range’)
Host specificity: A measure of the host range of a biological control agent on a scale ranging from ‘extreme specialist’ where the IBCA is only able to complete development on a single species or strain of its host (monophagous), to ‘generalist’, where many hosts ranging over several groups of organisms (polyphagous) can be used.
Hyperparasitoid: A parasitoid that uses another parasitoid as a host.
Inbreeding: The mating of genetically related individuals. Mating between relatives
Import permit (for a biological control agent): An official document authorising importation (of a biological control agent) in accordance with specified requirements.
Indirect effect (from the introduction of an exotic biocontrol agent): The effect that the introduction of exotic IBCAs has on other organisms not involving physical interaction with the biocontrol agent (effects can be positive, negative or neutral).
Infochemical: chemical that conveys information in an interaction between individuals, evoking in the receiver behavioural or physiological response that is adaptive to either one of the interacts or to both
Inoculative release: The introduction of a biological control agent with the aim of obtaining its establishment for long-term pest management, e.g. classical biological control.
Integrated Pest Management (IPM): A durable, environmentally and economically justifiable system in which damage caused by pests, diseases and weeds is prevented through the use of natural factors, which limit the population growth of these organisms, if needed supplemented with appropriate control measures (Gruys, P, personal communication 1976).

Integrated Pest Management (IPM): A pest population management system that utilises all suitable techniques in a compatible manner to reduce pest populations and maintains them at levels below those causing economic injury (Smith and Reynolds, 1966) (definition adopted by FAO).
Integrated Pest Management (IPM): there are many, strongly differing defenitions of IPM, the most important aspect of IPM is to try to manage pests as much as possible by use of natural factors like biological control and host plant resistance, and where chemical control is the last measure to turn to
Interbreeding: Breeding between different species
Intraguild predation: The killing and eating of species that otherwise use similar resources.
Introduction (of a biological control agent): The release of a biological control agent into an ecosystem where it did not exist previously.
Inundative release: The release of very large numbers of a mass-produced biological control agent with the expectation of achieving a rapid reduction of a pest population without necessarily achieving continuing impact or establishment of.
Invertebrate Biological Control Agent (IBCA): An invertebrate natural enemy used for pest management.
Learning: an adaptive change in behaviour after experience
Legislation: Any act, law, regulation, or other administrative order promulgated by a government.
Likelihood (in risk assessment): A qualitative description of probability or frequency, in relation to how likely it is that something will occur (see also risk').
Magnitude (in risk assessment): A qualitative descriptor of the size of the consequences if adverse or beneficial effects occur (see also 'risk')
Magnitude of risk of establishment: The area within which the introduced natural enemy is potentially able to establish, as a percentage of the area in which the exotic natural enemy will be licensed (e.g. a whole country or part of it)
Management or control of a pest: Suppression, containment or eradication of a pest population.
Microbial control: The use of micro-organisms (including viruses) as biological control agents.
Micro-organism: A protozoan, fungus, bacterium, virus or other microscopic self-replicating biotic entity.
Monophagous: An organism that attacks only one host species and is species specific.
Mutualism: An association between organisms of two different species in which each member benefits.
Native: Naturally occurring at area of proposed IBCA releases.
Natural enemy: An organism which lives at the expense of another organism and which may help to limit the population of this other organism. The term 'natural enemy' in this context includes parasitoids, parasites, predators and pathogens.
Naturally occurring: Refers to a component of an ecosystem or a selection from a wild population, not altered by artificial means.
Negligible risks: Risks which are of such little significance in terms of their likelihood and magnitude that they do not require active management and/or after the application of risk management do not need to be justified by counterbalancing benefits
Non-target organism : All organisms except the target organism.
Oligophagous: An organism that attacks a limited group of related hosts (e.g. up to 20 species in the same genus or subfamily.
Organism: Biotic entity capable of reproduction or replication, includes vertebrate and invertebrate animals, plants and micro-organisms.

Parasite: An organism which lives on or in a larger organism, feeding upon it.
Parasitoid: An insect parasitic only in its immature stages, killing its host in the process of its development, and free living as an adult.
Pathogen: Micro-organism causing disease.
Pathway: Any means that allows the entry or spread of an organism
Pest: A living organism which sometimes occurs in numbers inconvenient to man
Pest: Any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products.
Pest: Organism (plant, animal or protist) occurring in such numbers that it creates damage
Pest Risk Analysis: The process of evaluating biological or other scientific and economic evidence to determine whether an organism is a pest, whether it should be regulated, and the strength of any phytosanitary measures to be taken against it
Pest risk assessment: Evaluation of the probability of the introduction and spread of a pest and the magnitude of the associated potential economic consequences
Pest risk management: Evaluation and selection of options to reduce the risk of introduction and spread of a pest
Physiological (= fundamental) host range: The range of species a natural enemy can parasitize/feed on/infect in the laboratory (but see ‘ecological host range’)
Polyphagous: An organism that attacks a wide range of hosts from different subfamilies.
Predator: A natural enemy that preys and feeds on other animal organisms, more than one of which are killed during its lifetime.
Probability of adverse effects (from the release of biocontrol agents): The likelihood that an adverse effect will occur (e.g. reduction in the number of a non-target organism); in biological control, the likelihood that an adverse effect will occur is often a matter of space (dispersal) and time (survival and establishment).
Quarantine (of a biological control agent): Official confinement of biological control agents subject to phytosanitary regulations for observation and research, or for further inspection and/or testing.
Release (into the environment): Intentional liberation of an organism into the environment.
Release (of a consignment): Authorisation for entry after clearance.
Risk: The combination of the likelihood of occurrence and magnitude of consequences should the effects occur
Risk management options: Risk reduction actions that may be selected, alone or in combination, to reduce identified risks to an acceptable level (= risk mitigation)
Risk mitigation: see risk management options
Risk of adverse effect (from the release of biocontrol agents): Hazard times probability.
Seasonal inoculative releases: The release of mass-produced biological control agents with the expectation of achieving the reduction of a pest population during several generations without necessarily achieving continuing impact or establishment.
Specialist: See ‘host specificity’.
Suppression: The application of phytosanitary measures in an infested area to reduce pest populations.
Symbiosis: A close, prolonged association between organisms of different species that may, but does not necessarily, benefit each member.
Synomone: an allelochemical that is pertinent to the biology of an organism (organism 1) that evokes in the receiver (organism 2) a behavioural or physiological response that is adaptively favourable to both organism 1 and 2
Trophic levels: A functional classification of taxa within a community that is based on feeding relationships

Unacceptable risks: Risks of a type or level which the authority will not accept irrespective of any benefits that might accrue

Uncertainty: The estimated amount by which an observed value may differ from the true value due to incomplete or wrong information

References

Dicke, M. and Sabelis, M.W. (1988) Infochemical terminology: based on cost-benefit analysis rather than origin of compounds. Functional Ecology 2, 131-139.

Eilenberg, J., Hajek, A. and Lomer, C. (2001). "Suggestions for unifying the terminology in biological control" BioControl 46 (4): 387-400.

ERMA NZ (2000) Preparing information on risks, costs and benefits for applications under the Hazardous Substances and New Organisms Act 1996 (ER-TG-03-1 7/00), http://www.ermanz.govt.nz/resources/publications/pdfs/ER-TG-03-1.pdf (accessed 17 December 2004)

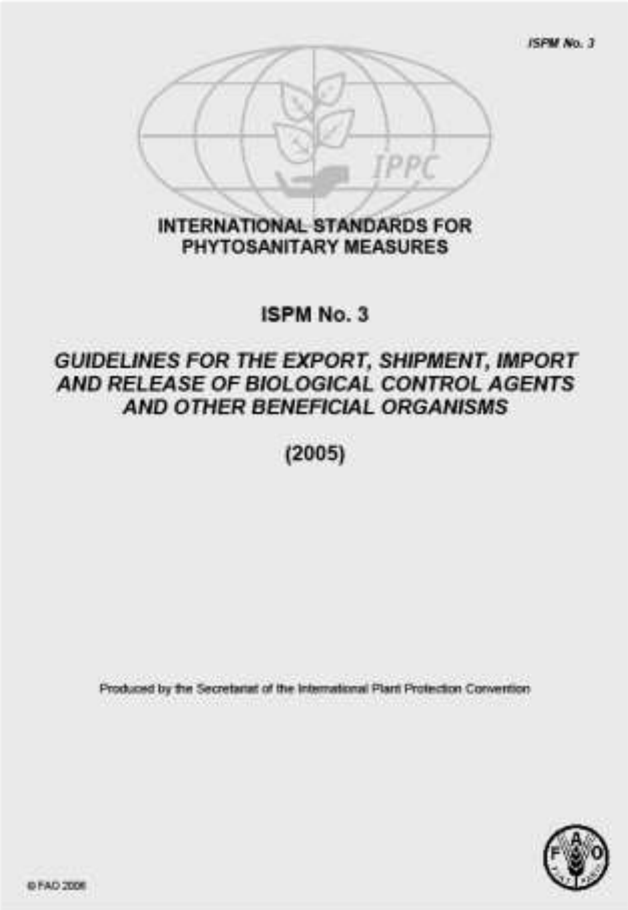
ERMA NZ (2004) A technical guide to identifying, assessing and evaluating risks, costs and benefits (ER-TG-05-1 03/04), http://www.ermanz.govt.nz/resources/publications/pdfs/ER-TG-05-01%200304%20DM%20Tech%20Gde.pdf (accessed 17 December 2004)

FAO (2001). Glossary of phytosanitary terms, international standards for phytosanitary measures. Secretariat of the International Plant Protection Convention, Food and Agriculture Organization of the United Nations, Rome, ISPM Pub. No. 5: 62 p.

Lenteren, J.C. van (2000). "Measures of Success in Biological Control Of Arthropods By Augmentation Of Natural Enemies". In: Measures of Success in Biological Control, S. Wratten and G. Gurr (eds.). Kluwer Academic Publishers, Dordrecht: 77-103. Version 4, J.C. van Lenteren, December 2001.

OECD, 2004. Guidance for Information Requirements for Regulation of Invertebrates as Biological Control Agents (IBCAs), Series on Pesticides No.21, ENV/JM/MONO(2004)1: 22 pp.

Appendix 3: Guidelines for the export, shipment, import and release of biological control agents 2005



Instead of presenting the full guideline here, you are invited to go to the following URL to download this guideline: www.fao.org

The guideline was developed by FAO in collaboration with IOBC.

An earlier version also prepared by FAO in collaboration with IOBC \ ("**Code of Conduct for Import and Release of Exotic Biological Control Agents"**) was published in 1995.

Appendix 4: EPPO standards on import and release of natural enemies

Instead of presenting the full standards here, you are invited to go to the following URL to download this guideline: http://archives.eppo.org/EPPOStandards/biocontrol.htm

You will find at this url:

PM 6/1(1)	First import of exotic biological control agents for research under contained conditions
PM 6/2(2)	Import and release of non-indigenous biological control agents

These standards have now been accepted by the 50 countries of the EPPO region (European Plant Protection Organization). The EPPO region is represented in the map below.

Appendix 5: Lists of biological control agents used in the EPPO region

Instead of presenting the lists here, you are invited to go to the following URL to download them: http://archives.eppo.org/EPPOStandards/biocontrol.htm

You will find at this url:

PM 6/3(4)
Lists of biological control agents widely used in the EPPO region version 2011

The lists are updated annually