The state of commercial augmentative biological control: plenty of natural enemies, but a frustrating lack of uptake

Joop C. van Lenteren

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The state of commercial augmentative biological control: plenty of natural enemies, but a frustrating lack of uptake

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Abstract Augmentative biological control concerns the periodical release of natural enemies. In commercial augmentative biological control, natural enemies are mass-reared in biofactories for release in large numbers to obtain an immediate control of pests. The history of commercial mass production of natural enemies spans a period of roughly 120 years. It has been a successful, environmentally and economically sound alternative for chemical pest control in crops like fruit orchards, maize, cotton, sugar cane, soybean, vineyards and greenhouses. Currently, augmentative biological control is in a critical phase, even though during the past decades it has moved from a cottage industry to professional production. Many efficient species of natural enemies have been discovered and 230 are commercially available today. The industry developed quality control guidelines, mass production, shipment and release methods as well as adequate guidance for farmers. However, augmentative biological control is applied on a frustratingly small acreage. Trends in research and application are reviewed, causes explaining the limited uptake are discussed and ways to increase application of augmentative biological control are explored.

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J. C. van Lenteren (✉)
Laboratory of Entomology, Wageningen University,
P.O. Box 8031, 6700 EH Wageningen, The Netherlands
e-mail: Joop.vanLenteren@wur.nl

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Introduction

Biological control is the use of an organism to reduce the population density of another organism. Biological control has been in use for about two millennia, and has become widely used in pest management since the end of the nineteenth century (DeBach 1964; van Lenteren and Godfray 2005). The following types of biological control can be distinguished: natural, conservation, inoculative (=classical) and augmentative biological control. Natural biological control is the reduction of pest organisms by their natural enemies and has been occurring since the evolution of the first terrestrial ecosystems some 500 million years ago. It takes place in all of the world's ecosystems without any human intervention, and, in economic terms, is the greatest contribution of biological control to agriculture (Waage and Greathead 1988). Conservation biological control consists of human actions that protect and stimulate the performance of naturally occurring natural enemies (Gurr and Wratten 2000). In inoculative biological control, natural enemies are collected in an exploration area (usually the area of origin of the pest) and then released in new areas where the pest was accidentally introduced. The aim is that the offspring of the released natural enemies build up populations which are large enough for suppression of pest populations during many subsequent years. This type of biological control has been used most frequently against introduced pests, which are presumed to have arrived in a new area without their natural enemies. As it was the first type of biological control practised widely, it is also called "classical" biological control (DeBach 1964). In augmentative biological control natural enemies are mass-reared in biofactories for release in large numbers to obtain an immediate control of pests. The history of commercial mass production and sale of natural enemies spans a period of roughly 120 years. In some areas of agriculture, such as fruit orchards, maize, cotton, sugarcane, soybean, vineyards and greenhouses, it has been an environmentally and economically sound successful alternative to chemical pest control (van Lenteren and Bueno 2003). Natural, conservation and inoculative biological control are generally carried out using public funding, whereas augmentative biological control is often a commercial activity because of the need of mass production and large scale regular releases of natural enemies.

Inoculative biological control is estimated to be used on 10% of land under cultivation (Bale et al. 2008) and, over the last 120 years, 165 pest species have been brought under long-term control (Cock et al. 2010). Cock et al. (2010) estimated that worldwide 170 species of invertebrate natural enemies are produced and sold globally for periodical release in augmentative biological control of more than 100 pest species on about 0.4% of land under cultivation. Augmentative biological control is operated by state-funded or commercial biofactories (van Lenteren and Bueno 2003).

Currently, augmentative biological control is in a critical phase, even though during the past decades it has moved from a cottage industry to professional production, which has identified many efficient species of natural enemies, developed quality control protocols, mass production, shipment and release methods, as well as adequate guidance for farmers (van Lenteren 2003; Cock et al. 2010). Large recent successes, such as the virtually complete replacement of pesticides by predatory mites to control thrips in Spain, show how well biological control can function (Merino-Pachero 2007) and literally saved vegetable production. However, this form of biological control is applied on a frustratingly small acreage, even though biological control has been considered the environmentally safest and most economically profitable form of pest management (e.g. DeBach and Rosen 1991; Cock et al. 2010). Thus, the question emerges "which factors prevent a much larger use of augmentative biological control?"

This paper first provides information about the 230 species of natural enemies which are used presently in augmentative biological control. Next, I explore why this type of biological control is not used more often. Finally, I summarize developments which are expected to lead to increased application of augmentative biological control.

Natural enemies used in augmentative biological control worldwide

Cock et al.'s (2010) database lists more than 170 species of invertebrate natural enemies that are used in augmentative biological control in Europe. Information about use of augmentative biological control outside Europe was obtained from recent literature and personal contacts. Although it was difficult to get hold of recent data for some areas of the world (e.g. several large Asian countries and Russia), Table 1 probably includes more than 95% of species used in augmentative releases, and allows a number of important conclusions to be drawn.

In 2010, no less than 230 species of invertebrate natural enemies—originating from ten taxonomic groups—were used in pest management worldwide. The majority of species belongs to the Arthropoda (219 out of 230 species = 95.2%) and only 11 species (one belonging to the Mollusca and ten belonging to the Nematoda) are non-arthropods. Within the arthropods, four taxonomic groups provided most natural enemies: first of all the Hymenoptera (52.2%, 120 species), next the Acari (13.1%, 30 species), followed by the Coleoptera (12.2%, 28 species) and Heteroptera (8.3%, 19 species) (Fig. 1). The large number of hymenopteran species used in augmentative control can be explained as follows: compared to predators, hymenopteran parasitoids are more specific and, therefore, have a much more

Table 1 Commercial availability of invertebrate natural enemies used worldwide in augmentative biological control, with region of use, year of first use and market value

Natural enemy	Classification	Region where used	Target(s)	Year of first use (estimated)	Market value
Adalia bipunctata	Coleoptera	Europe, North America	Aphids	1998	S
Aleochara bilineata	Coleoptera	Europe	Root flies	1995	S
Aeolothrips intermedius	Thysanoptera	Europe	Thrips	2000	S
Aleurodothrips fasciapennis	Thysanoptera	Europe	Diaspidids	1990	S
Amblyseius andersoni (=*potentillae*)	Acari	Europe, North America, Asia	Mites	1995	S
Amblyseius largoensis	Acari	Europe	Mites	1995	S
Amblyseius limonicus	Acari	Europe	Mites, thrips	1995	S
Amblyseius swirskii	Acari	Europe, Africa North and South, North and Latin America, Asia	Mites, thrips, whiteflies	2005	L
Amblyseius womersleyii	Acari	Asia	Mites	2005	L
Ampulex compressa	Hymenoptera	Europe	Cockroaches	1990	S
Anagrus atomus	Hymenoptera	Europe	Cicadellids	1990	S
Anagyrus dactylopii	Hymenoptera	Europe	Pseudococcids	1995	S
Anagyrus fusciventris	Hymenoptera	Europe	Pseudococcids	1995	S
Anagyrus pseudococci	Hymenoptera	Europe, North America	Pseudococcids	1995	S
Anaphes iole	Hymenoptera	Europe	Heteropterans	1990	S
Anthocoris nemoralis	Heteroptera	Europe, North America	Psyllids	1990	S
Anthocoris nemorum	Heteroptera	Europe	Psyllids, thrips	1992	S
Aphelinus abdominalis	Hymenoptera	Europe, Africa North, North America, Asia	Aphids	1992	M
Aphelinus asychis	Hymenoptera	Asia	Aphids	2005	S
Aphelinus mali	Hymenoptera	Europe	Aphids	1980	S
Aphelinus varipes	Hymenoptera	Europe	Aphids	2000	S
Aphidius colemani	Hymenoptera	Europe, Africa North and South, North America, Asia, Aus/NZ	Aphids	1991	L
Aphidius ervi	Hymenoptera	Europe, Africa North, North and Latin America, Asia	Aphids	1996	L
Aphidius gifuensis	Hymenoptera	Asia	Aphids	2005	M
Aphidius matricariae	Hymenoptera	Europe, North America	Aphids	1980	M
Aphidius transcaspinus	Hymenoptera	Africa South	Aphids	2005	M
Aphidius urticae	Hymenoptera	Europe	Aphids	1990	S
Aphidoletes aphidimyza	Diptera	Europe, Africa North and South, North America, Asia	Aphids	1989	L
Aphytis diaspidis	Hymenoptera	Europe	Diaspidids	1990	S
Aphytis holoxanthus	Hymenoptera	Europe	Diaspidids	1996	S
Aphytis lepidosaphes	Hymenoptera	Europe	Diaspidids	1985	S
Aphytis lingnanensis	Hymenoptera	Europe, Africa South, Aus	Diaspidids	1906	L
Aphytis melinus	Hymenoptera	Europe, North America, Aus	Diaspidids	1961	L
Aphytis spp. Peru	Hymenoptera	Latin America	Diaspidids	1990	M
Aprostocetus hagenowii	Hymenoptera	Europe	Cockroaches	1990	S

Table 1 continued

Natural enemy	Classification	Region where used	Target(s)	Year of first use (estimated)	Market value
Arrhenophagus albitibiae	Hymenoptera	Europe	Diaspidids	1990	S
Blastothrix brittanica	Hymenoptera	Europe	Coccids	2005	S
Bracon hebetor	Hymenoptera	Europe, North America	Lepidopterans	1980	S
Brontocoris tabidus	Heteroptera	Latin America	Lepidopterans	1990	S
Cales noacki	Hymenoptera	Europe	Whiteflies	1970	S
Carcinops pumilio	Coleoptera	North America	Dipterans	1990	S
Cephalonomia stephanoderis	Hymenoptera	Latin America	Coleopterans	1990	L
Chilocorus baileyi	Coleoptera	Europe, Aus	Diaspidids	1992	S
Chilocorus bipustulatus	**Coleoptera**	**Europe**	**Diaspidids**	**1992–2005**	**S**
Chilocorus circumdatus	Coleoptera	Europe, Aus	Diaspidids	1902	S
Chilocorus nigritus	Coleoptera	Europe, Africa South	Diaspidids	1985	S
Chrysoperla (=*Chrysopa*) *carnea*	Neuroptera	Europe, Africa North, North and Latin America, Asia	Aphids	1970	M
Chryosperla externa	Neuroptera	Latin America	Lepidopterans	1980	L
Chrysoperla spp. Peru	Neuroptera	Latin America	Aphids	1990	L
Chrysoperla rufilabris	Neuroptera	Europe, North America	Aphids	1970	S
Clitostethus arcuatus	Coleoptera	Europe	Whiteflies	1997	S
Coccidencyrtus ochraceipes	Hymenoptera	Europe	Diaspidids	1995	S
Coccidoxenoides perminutus	Hymenoptera	Europe, Africa North and South	Diaspidids, pseudococcids	1995	S
Coccinella septempunctata	Coleoptera	Europe	Aphids	1980	S
Coccophagus cowperi	Hymenoptera	Europe	Coccids, pseudococcids	1985	S
Coccophagus gurneyi	Hymenoptera	Europe	Diaspidids, pseudococcids	1985	S
Coccophagus lycimnia	Hymenoptera	Europe	Coccids	1988	S
Coccophagus pulvinariae	Hymenoptera	Europe	Coccids	1990	S
Coccophagus rusti	Hymenoptera	Europe	Coccids	1988	S
Coccophagus scutellaris	Hymenoptera	Europe	Coccids	1986	S
Coccophagus spp. Peru	Hymenoptera	Latin America	Coccids	1990	M
Coenosia attenuata	Diptera	Europe	Dipterans, whiteflies	1996	S
Comperiella bifasciata	Hymenoptera	Europe	Diaspidids	1985	S
Coniopteryx tineiformis	**Neuroptera**	**Europe**	**Aphids, mites, scales**	**1990–2005**	**S**
Conwentzia psociformis	**Neuroptera**	**Europe**	**Aphids, mites, scales**	**1990–2005**	**S**
Cotesia flavipes	Hymenoptera	Latin America	Lepidopterans	1974	L
Cotesia glomerata	Hymenoptera	Europe	Lepidopterans	1995	S
Cotesia rubecola	Hymenoptera	Europe	Lepidopterans	2000	S
Cryptolaemus montrouzieri	Coleoptera	Europe, Africa North and South, North and Latin America, Asia, Aus/NZ	Coccids, pseudococcids	1917	L
Cybocephalus nipponicus	Coleoptera	North America	Scales	2000	S

Table 1 continued

Natural enemy	Classification	Region where used	Target(s)	Year of first use (estimated)	Market value
Dacnusa sibirica	Hymenoptera	Europe, Africa North, North and Latin America, Asia	Dipterans	1981	L
Dalotia (*Atheta*) *coriaria*	Coleoptera	European, North America, Asia, Aus	Dipterans, thrips	2000	S
Delphastus catalinae	Coleoptera	Europe, North America	Whiteflies	1985	S
Delphastus pusillus	Coleoptera	Europe, North America	Whiteflies	1993	M
Digliphus begini	Hymenoptera	Latin America	Dipterans	2000	M
Dicyphus errans	Hymenoptera	Europe	Dipterans	2000	S
Diglyphus isaea	Hymenoptera	Europe, Africa North and South, North and Latin America, Asia	Dipterans	1984	L
Dicyphus hesperus	Hymenoptera	**Europe**	**Whiteflies**	**2000–2005**	**L**
Dicyphus hesperus	Hymenoptera	North America	Whiteflies	1995	M
Diomus spec.	Coleoptera	Europe	Scales	1990	S
Encarsia citrina	Hymenoptera	Europe	Diaspidids	1984	S
Encarsia guadeloupae	Hymenoptera	**Europe**	**Whiteflies**	**1990–2000**	**S**
Encarsia hispida	Hymenoptera	**Europe**	**Whiteflies**	**1990–2000**	**S**
Encarsia formosa	Hymenoptera	Europe, Africa North and South, North and Latin America, Asia, Aus/NZ	Whiteflies	1926	L
Encarsia protransvena	Hymenoptera	**Europe**	**Whiteflies**	**1990–2005**	**S**
Encarsia tricolor	Hymenoptera	Europe	Whiteflies	1985	S
Encyrtus infelix	Hymenoptera	Europe	Coccids	1990	S
Encyrtus lecaniorum	Hymenoptera	Europe	Coccids	1985	S
Episyrphus balteatus	Diptera	Europe	Aphids	1990	M
Eretmocerus corni	Hymenoptera	Latin America	Whiteflies	2000	S
Eretmocerus eremicus	Hymenoptera	**Europe**	**Whiteflies**	**1995–2002**	**L**
Eretmocerus eremicus	Hymenoptera	Africa North and South, North and Latin America, Asia	Whiteflies	1995	L
Eretmocerus mundus	Hymenoptera	Europe, Africa North and South, North and Latin America, Asia	Whiteflies	2001	L
Eretmocerus warrae	Hymenoptera	Aus/NZ	Whiteflies	2000	L
Euseius finlandicus	Acari	Europe	Mites	2000	S
Euseius scutalis	Acari	Europe	Mites	1990	S
Exochomus laeviusculus	Coleoptera	Europe	Aphids, scales	1988	S
Exochomus quadripustulatus	Coleoptera	Europe	Aphids, scales	2000	S
Feltiella acarisuga (=*Therodiplosis persicae*)	Diptera	Europe, North and Latin America	Mites	1990	M
Franklinothrips megalops (=*myrmicaeformis*)	Thysanoptera	Europe	Thrips	1992	S
Franklinothrips vespiformis	Thysanoptera	Europe, Asia	Thrips	1990	S
Galendromus (*Typhlodromus*) *occidentalis*	Acari	North America, Aus	Mites	1969	L

Table 1 continued

Natural enemy	Classification	Region where used	Target(s)	Year of first use (estimated)	Market value
Galeolaelaps (*Hypoaspis*) *aculeifer*	Acari	Europe, Africa North, North America, Asia, Aus/NZ	Dipterans, thrips, mites	1995	L
Geocoris punctipes	Heteroptera	North America	Lepidopterans, whiteflies	2000	S
Goniozus legneri	Hymenoptera	North America	Lepidopterans	1990	S
Gyranusoidea litura	Hymenoptera	Europe	Pseudococcids	1990	M
Harmonia axyridis	**Coleoptera**	**Europe**, except France where wingless *H. axyridis* are used	**Aphids**	**1995–2005**	**L**
Harmonia axyridis	Coleoptera	North America, Asia	Aphids	1990	L
Heterorhabditis bacteriophora	Nematoda	Europe, Africa North, North America, Aus	Coleopterans	1984	L
Heterorabditis bateriopora	Nematoda	Asia	Coleopterans	2000	L
Heterorhabditis megidis	Nematoda	Europe, North America	Coleopterans	1990	L
Heterorhabditis zealandica	Nematoda	Aus	Coleopterans	1990	L
Hippodamia convergens	Coleoptera	Europe	Aphids	1993	S
Hippodamia variegata	Coleoptera	Aus	Aphids	2000	S
Holobus flavicornis	Coleoptera	Europe	Mites	2000	S
Iphiseius (*Amblyseius*) *degenerans*	Acari	Europe, North America	Thrips	1993	M
Kampimodromus aberrans	**Acari**	**Europe**	**Mites**	**1960–1990**	**S**
Karnyothrips melaleucus	Thysanoptera	Europe	Diaspidids	1985	S
Lamyctinus coeculus	Chilopoda	Europe	Symphylans	1995	S
Leptomastidea abnormis	Hymenoptera	Europe, North America	Pseudococcids	1984	S
Leptomastix dactylopii	Hymenoptera	Europe, Africa North, North America	Pseudococcids	1984	M
Leptomastix epona	Hymenoptera	Europe	Pseudococcids	1992	S
Leptomastix histrio	Hymenoptera	Europe	Pseudococcids	1995	S
Lixophaga diatraea	Diptera	Latin America	Lepidipterans	1980	L
Lydella minense	Diptera	Latin America	Coleopterans	1990	L
Lysiphlebus fabarum	Diptera	Europe	Aphids	1990	S
Lysiphlebus testaceipes	Hymenoptera	Europe	Aphids	1990	S
Macrocheles robustulus	Acari	Europe	Dipterans, thrips, lepidoptera,	2010	L
Macrolophus caligonisus	Heteroptera	Europe	Whiteflies, lepidopterans	2005	M
Macrolophus pygmaeus (*nubilis*)	Heteroptera	Europe, Africa North and South	Whiteflies	1994	L
Mallada signata	Neuroptera	Aus	Aphids, thrips, lepidopterans, mealybugs, whiteflies, etc.	2000	L
Mesoseiulus longipes	Acari	North America	Mites	1989	L
Metaphycus flavus	Hymenoptera	Europe, North America	Coccids	1995	S
Metaphycus helvolus	Hymenoptera	Europe, Aus	Coccids	1943	S
Metaphycus lounsburyi (*bartletti*)	Hymenoptera	Europe, Aus	Coccids	1902	S

Table 1 continued

Natural enemy	Classification	Region where used	Target(s)	Year of first use (estimated)	Market value
Metaphycus stanleyi	Hymenoptera	Europe	Coccids	1990	S
Metaphycus swirskii	Hymenoptera	Europe	Coccids	1995	S
Metaphycus spp. Peru	Hymenoptera	Latin America	Coccids	1990	S
Metaseiulus occidentalis	Acari	Europe	Mites	1985	S
Meteorus gyrator	Hymenoptera	Europe	Lepdipterans	2005	S
Micromus angulatus	Neuroptera	Asia	Aphids	2005	S
Micromus tasmaniae	Neuroptera	Aus/NZ	Aphids, thrips, lepidopterans, whiteflies, etc.	2000	S
Microterys flavus	Hymenoptera	Europe	Coccids	1987	S
Microterys nietneri	Hymenoptera	Europe	Coccids	1987	S
Muscidifurax raptor	Hymenoptera	North and Latin America	Dipterans	1970	L
Muscidifurax raptorellus	Hymenoptera	Africa North, North America	Dipterans	1970	M
Muscidifurax zaraptor	Hymenoptera	Europe, North America	Dipterans	1982	M
Nabis pseudoferus ibericus	Heteroptera	Europe	Lepidopterans	2009	S
Nasonia vitripennis	Hymenoptera	Europe, North America	Dipterans	1970	S
Neochrysocharis formosa	Hymenoptera	Asia	Dipterans	1990	M
Neoseiulus (*Amblyseius*) *barkeri*	Acari	Europe	Thrips	1981	S
Neoseiulus (*Amblyseius*) *californicus*	Acari	Europe, Africa North and South, North and Latin America, Asia	Mites	1985	L
Neoseiulus (*Amblyseius*) *cucumeris*	Acari	Europe, Africa North and South, North and Latin America, Asia, Aus/NZ	Thrips, mites	1985	L
Neoseiulus (*Amblyseius*) *fallacis*	Acari	Europe, North America	Mites	1997	S
Neoseiulus wearnei	Acari	Aus	Mites	2000	S
Nephus includens	Coleoptera	Europe	Pseudococcids	2000	S
Nephus reunioni	Coleoptera	Europe	Pseudococcids	1990	S
Nesidiocoris tenuis	Heteroptera	Europe, Africa North, Asia	Whiteflies, lepidopterans	2003	L
Ooencyrtus kuvanae	Hymenoptera	Europe	Lepidopterans	1923	S
Ooencyrtus pityocampae	Hymenoptera	Europe	Lepidopterans	1997	S
Ophelosia crawfordi	Hymenoptera	Europe	Coccids, pseudococcids, margarodids	1980	S
Ophyra aenescens	Diptera	Europe, North America	Dipterans	1995	S
Opius pallipes	Hymenoptera	Europe	Dipterans	1980	S
Orgilus obscurator	Hymenoptera	Latin America	Lepidopterans	1990	L
Orius albidipennis	Heteroptera	Europe	Thrips	1993	S
Orius armatus	Heteroptera	Aus	Thrips	1990	S
Orius insidiosus	**Heteroptera**	**Europe**	**Thrips**	**1991–2000**	**L**
Orius insidiosus	Heteroptera	North and Latin America	Thrips	1985	L

Table 1 continued

Natural enemy	Classification	Region where used	Target(s)	Year of first use (estimated)	Market value
Orius laevigatus	Heteroptera	Europe, Africa North, Asia	Thrips	1993	L
Orius majusculus	Heteroptera	Europe	Thrips	1993	M
Orius minutus	Heteroptera	Europe	Thrips	1993	S
Orius strigicollis	Heteroptera	Asia	Thrips	2000	M
Orius tristicolor	**Heteroptera**	**Europe**	**Thrips**	**1995–2000**	**S**
Pachycrepoideus vindemiae	Hymenoptera	Latin America	Dipterans	1980	L
Paratheresia claripalpis	Hymenoptera	Latin America	Lepidopterans	1980	L
Pediobius foveolatus	Hymenoptera	North America	Coleopterans	1980	S
Peristenus digoneutis	Hymenoptera	North America	Heteropterans	1980	S
Pergamasus quisquiliarum	Acari	Europe	Symphylans	2000	S
Phasmarhabditis hermaphrodita	Nematoda	Europe	Snails	1994	S
Pheidole megacephala	Hymenoptera	Latin America	Colepterans	1990	L
Phytoseius finitimus	Acari	Europe	Mites	2000	S
Phytoseiulus longipes	Acari	Europe	Mites	1990	S
Phytoseiulus macropilis	Acari	Latin America	Mites	1980	L
Phytoseiulus persimilis	Acari	Europe, Africa North and South, North and Latin America, Asia, Aus/NZ	Mites	1968	L
Picromerus bidens	Heteroptera	Europe	Lepidopterans	1990	S
Podisus maculiventris	Heteroptera	Europe, North America	Coleopterans, lepidopterans	1996	S
Podisus nigrispinus	Heteroptera	Latin America	Lepidopterans	1990	S
Praon volucre	Hymenoptera	Europe	Aphids	1990	S
Prorops nasuta	Hymenoptera	Latin America	Coleopterans	1990	L
Prospaltella spp.	Hymenoptera	Latin America	Diaspidids	1990	M
Pseudaphycus angelicus	Hymenoptera	Europe	Pseudococcids	1990	S
Pseudaphycus flavidulus	Hymenoptera	Europe	Pseudococcids	1990	S
Pseudaphycus maculipennis	Hymenoptera	Europe	Pseudococcids	1980	S
Psyttalia concolor	Hymenoptera	**Europe**	**Dipteran**	**1968–2000**	**S**
Rhyzobius chrysomeloides	Coleoptera	Europe	Coccids	1980	S
Rhyzobius forestieri	Coleoptera	Europe	Coccids	1980	S
Rhyzobius (*Lindorus*) *lophanthae*	Coleoptera	Europe, North America	Coccids	1980	S
Rodolia cardinalis	Coleoptera	Europe	Margarodids	1990	S
Rumina decollata	Mollusca	Europe, North America	Molluscs	1990	S
Saniosulus nudus	Acaridae	Europe	Diaspidids	1990	S
Scolothrips sexmaculatus	Thysanoptera	Europe, North America	Mites, thrips	1990	S
Scutellista caerulea (*cyanea*)	Hymenoptera	Europe	Coccids	1990	S
Scymnus rubromaculatus	Coleoptera	Europe	Aphids	1990	S
Spalangia cameroni	Hymenoptera	Africa North, North and Latin America	Dipterans	1970	S

Table 1 continued

Natural enemy	Classification	Region where used	Target(s)	Year of first use (estimated)	Market value
Spalangia endius	Hymenoptera	North and Latin America, Aus	Dipterans	1970	L
Spalangia gemini	Hymenoptera	North America	Dipterans	1980	S
Spalangia nigroaenea	Hymenoptera	North America	Dipterans	1980	S
Steinernema carpocapsae	Nematoda	Europe, Africa North, North America, Asia	Coleopterans	1984	M
Steinernema glaseri	Nematoda	Europe	Coleopterans	2002	S
Steinernema feltiae	Nematoda	Europe, Africa North and South, North and Latin America, Aus/NZ	Sciarids	1984	L
Steinernema kraussei	Nematoda	Europe, North America	Coleopterans	2000	S
Steinernema riobrave	Nematoda	North America	Lepidopterans, coleopterans	2000	S
Stethorus punctillum	Coleoptera	Europe, North America, Asia	Mites	1984	S
Stratiolaelaps (*Hypoaspis*) *miles*	Acari	Europa, North America, Aus/NZ	Sciarids	1995	L
Stratiolaelaps (*Hypoaspis*) *scimitus*	Acari	Europa, Latin America	Sciarids	1990	L
Sympherobius fallax	Neuroptera	Europe	Pseudococcids	1994	S
Synacra paupera	Hymenoptera	Europe	Sciarids	2000	S
Telenomus remus	Hymenoptera	Latin America	Lepidopterans	1990	L
Tetracnemoidea brevicornis (=*Hungariella pretiosa*)	Hymenoptera	Europe	Pseudococcids, margarodids	1990	S
Tetracnemoidea peregrina (=*Hungariella peregrina*)	Hymenoptera	Europe	Pseudococcids, margarodids	1990	S
Tetrastichus coeruleus (*asparagi*)	Hymenoptera	Europe	Coleopterans	2000	S
Thripobius semiluteus	Hymenoptera	Europe, Aus	Thrips	1995	S
Trichogramma atopovirilia	Hymenoptera	Latin America	Lepidopterans	1990	S
Trichogramma bournieri	Hymenoptera	Africa South	Lepidopterans	2001	S
Trichogramma brassicae (=*maidis*)	Hymenoptera	Europe, North America	Lepidopterans	1980	S
Trichogramma cacoeciae	Hymenoptera	Europe	Lepidopterans	1980	S
Trichogramma carverae	Hymenoptera	Aus	Lepidopterans	1990	L
Trichogramma dendrolimi	Hymenoptera	Europe, Asia	Lepidopterans	1950	L
Trichogramma evanescens	Hymenoptera	Europe, Africa North, Asia	Lepidopterans	1975	L
Trichogramma exiguum	Hymenoptera	Latin America	Lepidopterans	1990	L
Trichogramma galloi	Hymenoptera	Latin America	Lepidopterans	1980	L
Trichogramma minutum	Hymenoptera	North America	Lepidopterans	1970	S
Trichogramma nerudai	Hymenoptera	Latin America	Lepidopterans	1990	S
Trichogramma ostriniae	Hymenoptera	North America, Asia	Lepidopterans	1980	S
Trichogramma pintoi	Hymenoptera	Latin America	Lepidopterans	1990	M
Trichogramma platneri	Hymenoptera	North America	Lepidopterans	1990	S
Trichogramma pretiosum	Hymenoptera	North and Latin America, Aus	Lepidopterans	1974	L

Table 1 continued

Natural enemy	Classification	Region where used	Target(s)	Year of first use (estimated)	Market value
Trichogrammatoidea cryptophlebiae	Hymenoptera	Aus	Lepidopterans	1990	L
Typhlodromus athiasae	Acari	Europe	Mites	1995	S
Typhlodromus doreenae	Acari	Europe	Mites	2003	S
Typhlodromus pyri	Acari	Europe	Mites	1990	S
Typhlodromips montdorensis	Acari	Europe, Aus	Thrips, mites	2003	L
Urolepis rufipes	Hymenoptera	North America	Dipterans	1990	S

Key: Market value: L = large (hundred thousand to millions of individuals sold per week), M = medium (ten thousand to a hundred thousand of individuals sold per week), S = small (hundreds to a few thousand of individuals sold per week); Africa North = North of Sahara, Africa South = South of Sahara, North America = Canada + USA, Aus = Australia, NZ = New Zealand; bold entries natural enemies: no longer in use

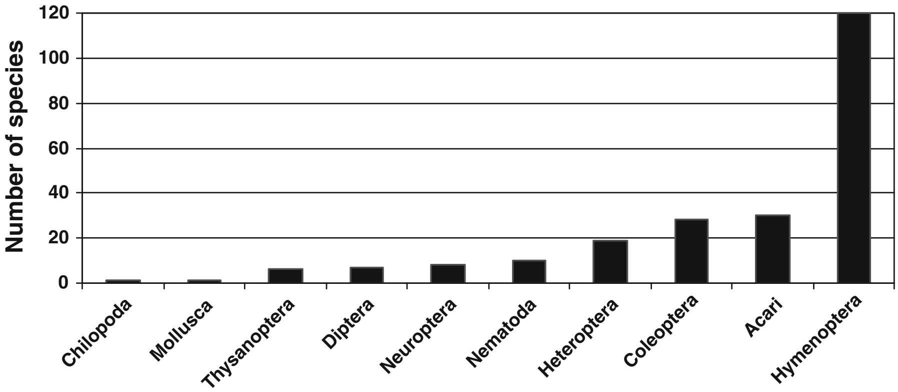

Fig. 1 Taxonomic groups providing natural enemies used in commercial augmentative biological control from 1900 to 2010

restricted host range, which is considered important in preventing undesirable side effects (e.g. Bigler et al. 2006). Acarid predators are popular because they can easily be mass reared, they can be released by mechanical means, may control several pest species, do not spread actively over large distances and are relatively small. The last two characteristics help to prevent negative effects on non-target species. An example of a recent acarid species becoming very popular in use is *Amblyseius swirskii* (Calvo and Belda 2007; Calvo et al. 2011).

The first species used in augmentative biological control were a hymenopteran (*Metaphycus lounsburyi* (*bartletti*)) and a coleopteran (*Chilocorus circumdatus*), both in 1902 (Table 1). During the initial seven decades of augmentative biological control (1900–1969) 11 species (0.11 year^{-1}) became available, mainly hymenopterans (seven species). From 1970 onwards the number of new species becoming commercially available increased from 1.2 year^{-1} (1970–1979), to 5.5 year^{-1} (1980–1989), culminating in 10.9 year^{-1} during the 1990s, and decreased to 4.2 year^{-1} during the first decade of the 21st century (Fig. 2).

The strong increase in newly available natural enemies during the period 1970–1999 is caused by several factors. First of all, many pests developed resistance to insecticides after the initiation of large scale pesticide applications in the 1950s. This called for renewed use of already known biological control agents. And, if one natural enemy was used against an insecticide resistant pest, other pests in the same

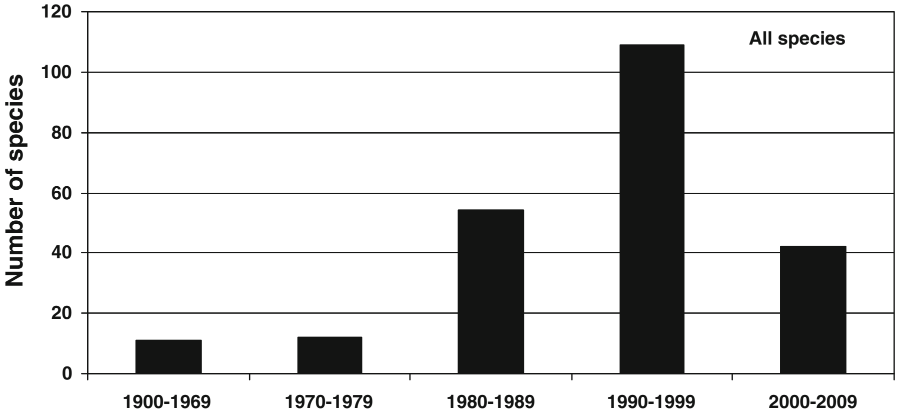

Fig. 2 Number of natural enemy species becoming available per time period

crop also needed to be managed with non-chemical control methods, including biological control (Hussey and Bravenboer 1971). This stimulated a search for new natural enemies and the development of Integrated Pest Management (IPM) (van Lenteren and Woets 1988; Parrella et al. 1999). For crops produced in greenhouses, biological control made it possible to use honey bees and bumble bees for pollination. Due to the great success of this type of pollination (reduced labour costs and, above all, increased production), growers were even more motivated to use biological control—not only for pests, but also for diseases (Albajes et al. 1999). At the same time, environmental and health concerns about pesticides encouraged design and implementation of IPM and biological control worldwide.

There are two reasons for the decrease in use of new natural enemy species after 2000: (1) efficient natural enemies were available for most of the pests in the agroecosystems where augmentative control is popular, and (2) stronger regulation of import of exotic natural enemies and registration of biological control agents has negatively affected their market penetration (Bolckmans 1999).

The relationship of number of species becoming available over time for the four taxonomic groups that provided most species of natural enemies is similar to that of all species combined (Fig. 3). They all show a peak during the period 1990–1999, with one obvious difference: heteropterans have only been used in augmentative control from 1990 onwards.

Most natural enemy species (75%; 173 of 230 species) are produced in low or medium numbers per week (hundreds to a hundred thousand). This can be explained by their application in situations where only low numbers are needed (e.g. use in private gardens, hospitals, banks, shopping malls etc.), or the fact that they are only occasionally needed in large cropping systems (e.g. in greenhouses for control of minor pests). An example of a taxonomic group mainly used in niche markets is the Coleoptera, 26 of the 28 species are produced in small numbers (Table 1). Natural enemies produced in numbers of more than 100,000 per week (25%; 57 of 230 species) can be separated in two groups: species where very large numbers need to be released per unit area in order to obtain sufficient control (acarids and nematodes), and species that are released at a low density on very large areas (coleopterans, heteropterans and hymenopterans in crops like citrus, sugar cane and maize). This means that simply looking at the numbers produced does not give a good indication of the market value of a species.

In Table 2 the 25 most often used natural enemy species are listed. These species make up more than 90% of the approximately €300 million of the total world market at end-user level (Bolckmans 2008; Cock et al. 2010). When expressed in sales volume, the most important commercial markets for natural enemies are greenhouse crops in The Netherlands, the UK, France and Spain, followed by the USA (Fig. 4). Together, these countries account for about two-thirds of the total market (Bolckmans 1999). Nevertheless, Africa, Asia and Latin America represent significant and growing markets. The commercial market for field crops is tiny compared to the greenhouse market.

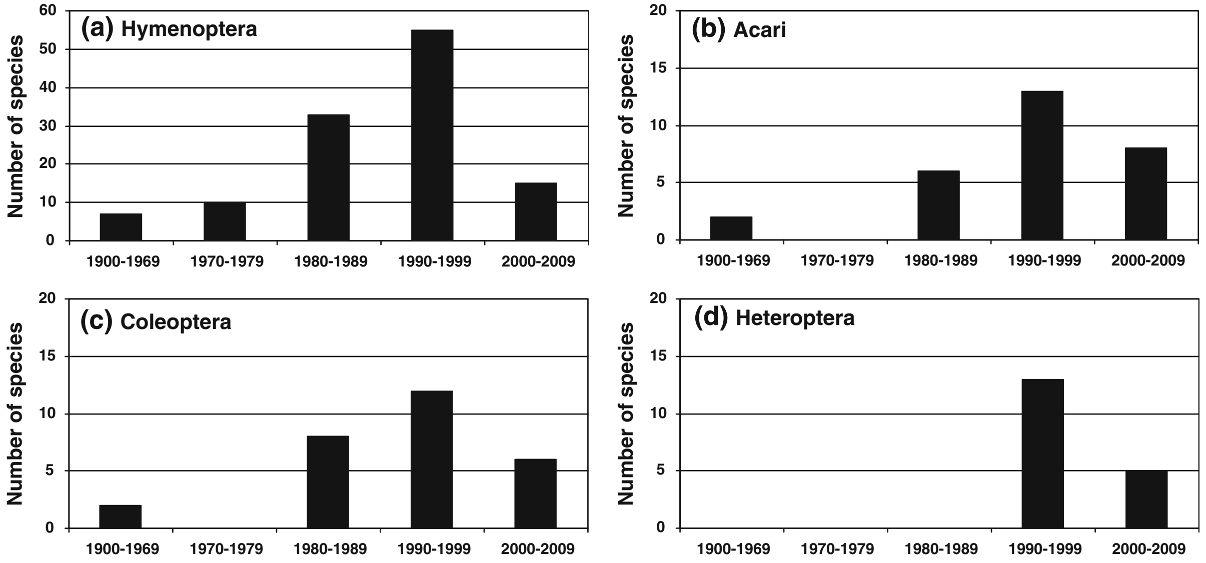

Fig. 3 Number of natural enemy species becoming available per time period for the four taxonomic groups which provided the majority of biological control agents: **a** Hymenoptera, **b** Acari, **c** Coleoptera and **d** Heteroptera

The agents used in augmentative biological control may be indigenous or exotic. Where they are exotic, they should—under best practice—undergo an environmental risk assessment, which is now common practice in several countries (Cock et al. 2010; van Lenteren et al. 2003, 2006). Due to the concern about import and release of exotic natural enemies and the increased evaluation and registration demands, there is a trend nowadays to first look for indigenous natural enemies when a new exotic pest establishes itself. This is clearly illustrated by the number of natural enemies that were used for the first time in Europe in previous decades (Fig. 5). Until 1970, the only two species commercially used in Europe were exotics. During the following three decades, more new exotic species (77) were used than indigenous species (58). In the last decade, this trend changed and for the first time more indigenous species (18) were commercialized than exotic species (6).

Of the natural enemy species commercially allowed for use in Africa, more than 90% results from material collected in and—initially mass reared on—other continents (Table 1). A similar situation exists in Canada, Japan, Mexico and South Korea. In Australia, New Zealand and the United States almost equal numbers of indigenous and exotic natural enemies are used. The situation is quite different in several South and Central American countries (e.g. Argentina, Brazil and Cuba), where most of the natural enemies used in augmentative biological control are indigenous species (Table 1).

Table 1 shows another interesting development: not only are indigenous natural enemy species increasingly evaluated for first use, but also several of the popular exotic biological control agents have recently been replaced by indigenous species. The developments on the European market clearly illustrate this: nine exotic species have been substituted by indigenous species. Two important examples are the replacement of *Eretmocerus eremicus* by *E. mundus* and the replacement of *Orius insidiosus* by *O. laevigatus*.

Commercial augmentative biological control: the current state of play

Biological control is the most environmentally safe and economically profitable pest management method, which is illustrated by the data for biological and chemical control given in Table 3. In biological control, we still have hundreds of thousands of species of natural enemies waiting to be discovered, and finding a new biological control agent is characterized by a very high success ratio compared to the ratio obtained in chemical control. In chemical control,

Table 2 The most important invertebrate biological control agents used in augmentative biological control ranked by number of countries in which each is used (modified after Cock et al. 2010)

Biological control agent	Family	Target(s)	No. of countries where used	Year of first use
1. *Amblyseius swirskii*	Phytoseiidae	Whiteflies, thrips, mites	>20	2005
2. *Aphidius colemani*	Braconidae	Aphids	>20	1991
3. *Aphidoletes aphidimyza*	Cecidomyiidae	Aphids	>20	1989
4. *Dacnusa sibirica*	Braconidae	Leafminers	>20	1981
5. *Diglyphus isaea*	Eulophidae	Leafminers	>20	1984
6. *Encarsia formosa*	Aphelinidae	Whiteflies	>20	1926
7. *Macrolophus pygmaeus* (=*nubilis*)	Miridae	Whiteflies	>20	1994
8. *Neoseiulus cucumeris* (=*Amblyseius cucumeris*)	Phytoseiidae	Thrips	>20	1985
9. *Phytoseiulus persimilis*	Phytoseiidae	Mites	>20	1968
10. *Steinernema feltiae*	Steinernematidae	Sciarids	>15	1984
11. *Aphidius ervi*	Braconidae	Aphids	>15	1996
12. *Orius laevigatus*	Anthocoridae	Thrips	>15	1993
13. *Cryptolaemus montrouzieri*	Coccinellidae	Coccids, pseudococcids	>15	1989
14. *Galeolaelaps aculeifer* (=*Hypoaspis aculifer*)	Laelapidae	Sciarids	>15	1996
15. *Feltiella acarisuga* (=*Therodiplosis persicae)*	Cecidomyiidae	Mites	>15	1990
16. *Leptomastix dactylopii*	Encyrtidae	Pseudococcids	>15	1984
17. *Stratiolaelaps miles* (=*Hypoaspis miles*)	Laelapidae	Sciarids	>15	1995
18. *Aphelinus abdominalis*	Aphelinidae	Aphids	>10	1992
19. *Heterorhabditis bacteriophora*	Heterorhabditidae	Coleopterans	>10	1984
20. *Heterorhabditis megidis*	Heterorhabditidae	Coleopterans	>10	1990
21. *Neoseiulus californicus* (=*Amblyseius californicus*)	Phytoseiidae	Mites, thrips	>10	1985
22. *Eretmocerus eremicus*	Aphelinidae	Whiteflies	>10	1995
23. *Eretmocerus mundus*	Aphelinidae	Whiteflies	>10	2001
24. *Episyrphus balteatus*	Syrphidae	Aphids	>10	1990
25. *Trichogramma evanescens*	Trichogrammatidae	Lepidopterans	>10	1975

the success ratio has decreased from 1:50,000 in 1995 to 1:140,000 in 2008, while developmental costs have strongly increased during the past decades (McDougall 2010). The developmental costs for biological control are a fraction of those for chemical control. The time to develop a product is the same for both control methods. The benefit/cost ratio for inoculative biological control is much higher than for chemical control. For commercial augmentative biological control it is similar, but higher if we take indirect costs for chemical control into account which are related to environmental pollution and human health problems (Pimentel et al. 1980; Pimentel 2009). The risks of resistance are low or non-existent in biological control, while they are high in chemical control. High specificity and the lack of harmful side effects are characteristic for biological control agents. More than 7,000 introductions involving almost 2,700 species of exotic arthropod agents for control of arthropod pests in 196 countries or islands during the past 120 years rarely have resulted in negative environmental effects (Cock et al. 2009, 2010), although there are some exceptions (Howarth 1991; Louda et al. 2003; van Lenteren et al. 2006) including the recent case of the Asian lady beetle (*Harmonia axyridis*) (van Lenteren et al. 2008). Application of chemical pesticides kills many species of nontarget organisms within and outside the agro-ecosystem, and may result in various side-effects, including unexpected, indirect and long-term effects on the environment and on the health of farmers and consumers (Pimentel et al. 1980; Pimentel 2009).

Before discussing the state of play in commercial augmentative biological control, I summarize the

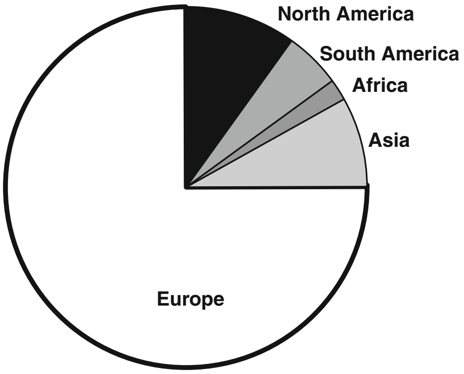

Fig. 4 The 2008 market share of commercial augmentative biological control by regions (after Cock et al. 2009)

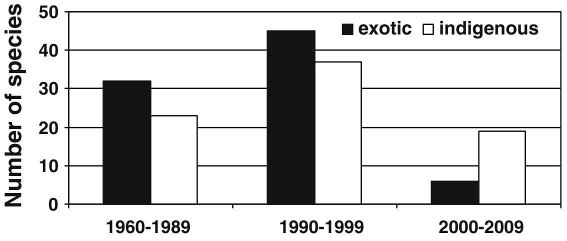

Fig. 5 Numbers of exotic (black) and indigenous (white) invertebrate natural enemies introduced to the European market over time

Table 3 Comparison of aspects related to the development and application of chemical and biological control

	Chemical control[a]	Biological control[b]
Number of "ingredients" tested	>3.5 million	3,500
Success ratio	1:140,000	1:10
Developmental costs	256 million US$	2 million US$
Developmental time	10 years	10 years
Benefit/cost ratio	2:1	2.5–20:1
Risks of resistance	Large	Nil/small
Specificity	Small	Large
Harmful side-effects	Many	Nil/few

[a] Main sources for data McDougall (2010), Pimentel et al. (1980), Pimentel (2009)

[b] Main sources for data Bale et al. (2008), Cock et al. (2009, 2010), Pimentel et al. (1980), Pimentel (2009)

situation for natural and inoculative control to make clear that biological control plays a very important role in today's agriculture and forestry. Natural biological control occurs on 89.5 billion ha of the world's ecosystems (land with vegetation), of which 44.4 billion ha is used for some form of agricultural activity (including forestry and grassland). Natural and inoculative biological control contribute to managing indigenous and alien pest problems in natural and managed ecosystems, and also in controlling vectors of human and veterinary diseases. The most widely used natural enemies in inoculative weed and insect control (e.g. *Aphelinus mali*, *Aphytis lingnanensis*, *Cotesia flavipes*, *Cryptolaemus montrouzieri*, *Rodolia cardinalis*, *Teleonemia scrupulosa*) have been introduced in more than 20 countries/regions worldwide and resulted in permanent control of the pest (Cock et al. 2009, 2010). Inoculative biological control is used on 350 million ha (10% of land under cultivation). The "ecosystem service" provided by natural and inoculative biological control has an estimated value of at least 400 billion US$ per year (Costanza et al. 1997), which is enormous, even when compared with the annual amount of 30 billion US$ spent on chemical pest control (Crop Life International 2008). The impact of biological control is creating and sustaining public goods, such as food security, food quality, reduced pesticide use, human health (especially for farmers and farm workers), invasive alien species control, protection of biodiversity and maintenance of ecosystem services (Cock et al. 2010).

Compared to natural and inoculative biological control, commercial augmentative biological control is applied on a very limited scale, i.e. on only 16 million ha, which is 0.4% of cultivated land with crops on which this type of control could be used. Worldwide, some 30 "large" commercial producers are active (Bolckmans 2008), of which 20 are located in Europe. "Large" means that more than ten people are employed. In addition to these larger producers, it is estimated that about 500 small commercial producers are active. Fewer than five companies employ more than 50 people. The largest company has currently (2011) about 600 people employed. Producers organized themselves in different associations: in Europe in the International Biocontrol Manufacturers Association (IBMA), in North America in the Association of Natural Biocontrol Producers (ANBP), in Australia in Australasian Biological Control (ABC) and in Brazil in the Brazilian Association of Biological Control (ABCbio).

Given the large numbers of natural enemy species commercially available and the many positive characteristics of biological control specified above, the question emerges what the causes of the frustrating lack of uptake of augmentative biological control are. In the next section, the various and wide-ranging explanations for the limited use are discussed.

Reasons for the limited use of commercial biological control

Attitude of the pesticide industry

The pesticide industry is not interested in biological control, because natural enemies cannot be patented, cannot be stored for long periods, act very specifically, can often not be combined with chemical control and need extra training of sales personnel and farmers. The pesticide industry is not particularly concerned either with sustainable, long-term solutions for pest control as patent periods on pesticides are limited. Their concern is to develop and market new insecticides. This will be a continuous threat to biological control, although work of the International Organization for Biological Control (IOBC) has resulted in a European Union (EU) demand of testing side-effects on natural enemies for new pesticides. This knowledge tells which biological control agents will be killed when using certain pesticides. The side-effect tests initially developed by IOBC and, later, in collaboration with the European Plant Protection Organization (EPPO) are now required elements of the EU registration procedure for pesticides (EPPO 2003). The attitude of the chemical industry has somewhat improved recently and some companies are even producing natural enemies. The reason for this is that the chemical industry desperately needs biological control, because with chemical control alone it is no longer possible to control all pests (Merino-Pachero 2007).

A more serious problem of pesticides is that they are unjustly cheap because society ends up paying for the so-called indirect costs created by pesticide use such as death of nontarget organisms, human health problems, environmental pollution and interference with ecosystem functions (Costanza et al. 1997; Pimentel 2009). Taking these costs into account, pesticides should be at least three times more expensive and, as a result, realistic pricing of pesticides would more often lead to a choice for biological control (Pimentel et al. 1980; Pimentel 2009).

Attitude of farmers

The current attitude of many farmers concerning pest control is that a crop cannot be grown without use of pesticides. This view is correct for many of the crops used in today's agriculture, because they have been selected under a blanket of pesticide applications with as main goal to identify cultivars with highest yields (food) or best appreciated cosmetic value (flowers). As a result, it will require a lot of creativity to accomplish a drastic change in the mind-set of pesticide addicted farmers and the replacement of poison dependent crop cultivars by disease and pest resistant crop cultivars.

Attitude of governmental institutions

Next, there is seldom a national or international policy to enforce the use of sustainable solutions for pest control. Farmers are of the opinion that registered pesticides are safe for the environment and for man, so there is no incentive for them to change. The industry, understandably, is not interested in complicated IPM systems with low profit margins. Therefore, it seems that only governments can effect change by enforcing use of non-chemical pest control (but see the remark below about the role of food retailers). European governments were provided as early as 1992 with important background information in the form of the report “Ground for Choices: four perspectives for the rural areas in the European Community” (Latesteijn 1992). This report showed that with good farming practices an overall reduction in pesticide volume used of more than 90% could be reached. In this same period, IOBC had developed and tested IPM programmes for a number of crops in which use of pesticides was even lower (e.g. van Lenteren et al. 1992). Although governments often react positively when asked how they think about biological and integrated control, such reactions can almost exclusively been put into the category “paying lip service”, because financial, long-term support for research and implementation is not provided. One would expect governments to strongly stimulate use of environmentally friendly forms of pest management, because there is an overwhelming amount of information showing that agriculture is a major source of pollution and that chemical pesticides have serious negative effects on biodiversity and (natural) biological control. For example, Geiger et al. (2010) conclude: "… that despite decades of European policy to ban harmful pesticides, the negative effects of pesticides on wild plant and animal species persist, at the same time reducing the opportunities for biological pest control. If biodiversity is to be restored in Europe and opportunities are to be created for crop production utilizing biodiversity-based ecosystem services such as biological pest control, there must be a Europe-wide shift towards farming with minimal use of pesticides over large areas." Apparently, the tide is turning: the European Commission (EC) is aiming at replacement of chemical pesticides by non-chemical means of pest management (see below).

Influence of guidelines and regulations

Another factor frustrating application of biological control is the increasing amount of guidelines and regulations. Some of these regulations like the "Guidelines for the export, shipment, import and release of biological control agents and other beneficial organisms" (IPPC 2005), the guidelines for Environmental Risk Assessment mentioned earlier in this paper, and national regulations for import and release of biological control agents may delay implementation of biological control (Bolckmans 1999). Most of these guidelines could and should be drastically simplified and harmonized, which will result in application of more biological control. But the future of biological control might be really threatened by the plans concerning benefit sharing under the Convention of Biological Diversity (CBD). Under this convention countries have sovereign rights over their biodiversity. Agreements governing the access to these resources and the sharing of the benefits arising from their use need to be established between involved parties (i.e. Access and Benefit Sharing (ABS)). This also applies to species collected for potential use in biological control. Recent applications of CBD principles have already made it difficult or impossible to collect and export natural enemies for biological control research in several countries (Cock et al. 2010). The CBD was required to agree a comprehensive ABS process in 2010. In preparation for this, IOBC has prepared a position paper (Cock et al. 2010) in which the practice of biological control in relation to the principles of ABS is described and illustrated extensively by case studies and successes obtained with biological control. During the 10th Conference of the Parties to the Convention on Biological Diversity (18–29 October 2010, Nagoya, Japan) the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity was adopted (CBD 2010; UN 2010). Article 8 'Special Considerations' of the Nagoya Protocol states (UN 2010):

> In the development and implementation of its access and benefit-sharing legislation or regulatory requirements, each Party shall:
>
> (a) Create conditions to promote and encourage research which contributes to the conservation and sustainable use of biological diversity, particularly in developing countries, including through simplified measures on access for non-commercial research purposes, taking into account the need to address a change of intent for such research;
> (b) Pay due regard to cases of present or imminent emergencies that threaten or damage human, animal or plant health, as determined nationally or internationally. Parties may take into consideration the need for expeditious access to genetic resources and expeditious fair and equitable sharing of benefits arising out of the use of such genetic resources, including access to affordable treatments by those in need, especially in developing countries;
> (c) Consider the importance of genetic resources for food and agriculture and their special role for food security.

Collection of natural enemies is not specifically mentioned as non-commercial research in this protocol and all countries involved in a natural enemy exploration project would have to prepare their legislation in such a way that exploration can be treated as non-commercial. It is expected that development of such legislation may form a time-consuming hurdle. If it is accepted that biological control is non-commercial research, simplified measures for ABS should facilitate biological control research.

Furthermore, the use of biological control to address emergencies and the needs of food and agriculture should also be facilitated.

Attitude of biological control community

What about the biological control research community itself? Researchers and practitioners of biological control are not particularly good at lobbying and promoting the impressive benefits of biological control, they do not blow their own trumpet, they have not learned to defend their work forcefully, they often forget to illustrate the fantastic and permanent results obtained with inoculative biological control, thereby limiting discussions to the as yet restricted application of commercial biological control. Biological control workers are their own worst natural enemy!

It is also sad and disappointing that entomologists and biological control researchers have the peculiar habit of being over critical about their own work. An example is a publication by Collier and van Steenwyk (2004) with the title: "A critical evaluation of augmentative biological control". Yet, the article does not present an evaluation of augmentative biological control, but, instead, the authors evaluated some research articles, and neglected papers on practical application. What's more, the article is not a critical evaluation of augmentative biological control in general, but is mainly limited to a few experimental situations in the USA. There are, however, plenty examples of successful practical augmentative programs both within and outside the USA (see e.g. Gurr and Wratten 2000). Moreover, because the authors try to answer their questions with unsuitable data, their conclusions are in clear disagreement with the current state of affairs in the field of augmentative biological control illustrated above. An unforeseen aspect of such papers is that policymakers, politicians and the pesticide industry may use the—erroneous—information to show how poorly commercial biological control performs (van Lenteren 2006).

Factors stimulating the use of biological control

Next to the factors hampering application, there are significant developments which will stimulate the use of biological control.

Arthropod resistance to pesticides

Ongoing development of resistance to pesticides by arthropods, and increasing demands concerning the environmental and health effects of pesticides will make their development more difficult and costly. We can already see a stabilization and decrease of pesticide use in Europe and North America. As a result of the impossibility to control certain pests with chemicals, we see dramatic shifts from complete chemical control to mainly biological control in greenhouse vegetable production in North-West Europe, Spain and China, to name but a few (Merino-Pachero 2007; Pilkington et al. 2010).

Residue demands by food retailers and supermarket chains

An important development amongst food retailers and supermarket chains is that they are increasingly demanding pesticide poor or pesticide free food and prescribe pest management protocols to farmers. Supermarket chains, farmers and crop protection specialists collaborate in GLOBALGAP, a private sector body that sets standards for the certification of agricultural products around the globe. One of the GLOBALGAP guidelines concerns IPM, and biological control together with other types of non-chemical control form an essential part of this guideline (http://www.globalgap.org). These GLOBALGAP guidelines are often more restrictive about the use of conventional chemical pesticides than national or international regulations.

Attitude of consumers

Although it is generally believed that consumers prefer biological control above other pest control methods, this is rarely documented. In Canada, a professionally designed survey was conducted—a worldwide premiere—to determine the perception to the use of biological control as a means of pest management. The respondents clearly believed that foods produced using biological control were safer than those using synthetic insecticides. The majority of respondents felt that there would be less risk associated with consuming food when biological control agents, rather than synthetic chemical means, were used to control pests (McNeil et al. 2010).

Change in attitude of governmental institutions

A recent example of how governmental institutions, in this case in Europe, can stimulate the use of biological control is the following. The European Commission (EC) is putting non-chemical forms of pest control high on the research and implementation agenda with the main goal to make agriculture less dependent on conservative synthetic chemical control (EU Directive 2009/128/EC; EC 2010). Again, due to EC policy, it is anticipated that 750 of 1,000 active ingredients used in chemical control will be phased out in the coming years. Furthermore, a substitution principle will be applied to new pesticides, by which the economically sound and environmentally safest agents will get priority for registration. In addition, each EC member country has to develop a national action program for IPM before 2014, and application of IPM, including biological control, will become the compulsory crop protection method from 2014 onwards. These measures are expected to form an important incentive for biological control.

This change in attitude currently perceived in Europe is, fortunately, not unique. In the past, environmental and health concerns have led to sustainable approaches of pest control in various areas worldwide as reviewed by Peshin et al. (2009).

Various other factors stimulating use of biological control

Implementation of biological control is assisted significantly by meeting the following basic conditions: (1) availability of a complete IPM programme for a crop, (2) total costs of IPM programme similar to costs for chemical control programme, (3) existence of reliable, independent extension service not compromised by the pesticide industry, and (4) support of application of non-chemical forms of pest management by governmental institutions. Another factor which helps implementation of biological control is the provision of sufficient and long term research funding. At present, funding of biological or IPM research is a minimal fraction (<1%) of the funding for research in chemical control.

Application of the substitution principle whereby environmentally hazardous pesticides are replaced by the ecologically best alternatives will also increase application of biological control. In other cases, simply banning of the worst pesticides by governmental decree may lead to restoration of natural biological control (Kenmore 1991; Oka 1991) and provide better opportunities for augmentative biological control.

Moreover, realistic pricing of chemical control to compensate for indirect, societal and environmental costs (Pimentel 2009), would make the competition with sales of biological control agents fairer. In fact, several countries (e.g. Denmark, Norway, Sweden) are levying pesticide taxes, which are partly used for development of IPM programmes and incentives for farmers to encourage “low-pesticide” farming. These pesticide taxes also resulted in an immediate decrease in use of pesticides (Cannell 2007).

Conclusions

During the past 120 years, a large number of natural enemies has been collected and evaluated for use in augmentative biological control programmes. Particularly during the last 30 years many efficient species have been identified and currently at least 230 species are commercially available globally. Today, the commercial biological control industry is well organized, has developed mass production, shipment and release methods as well as adequate guidance for farmers. The industry has intensively collaborated with the public research sector in design of quality control programmes, which are applied during natural enemy production and shipment. The industry also cooperated in preparing environmental risk assessment methods for biological control agents. In several areas of agriculture augmentative biological control has obtained considerable successes and is now a reliable and appreciated element of IPM programmes. Despite all this progress, augmentative biological control is applied on a frustratingly small acreage.

Different reasons explain the slow uptake. The pesticide industry considers biological control as cumbersome and of restricted use, most farmers have become pesticide addicted during the past 60 years, governmental institutions do not enforce or stimulate non-chemical pest control, and many regulations concerning the collection and application of biological control agents delay or even prohibit their use.

Recent developments may, however, lead to a promising future for augmentative biological control.

In addition to the ever ongoing development of resistance of pests to pesticides resulting in a need for alternative control methods, requirements of residue free food by supermarkets and consumers, prioritizing use of IPM by governmental institutions like the European Union and termination of pesticides subsidies, will all result in better possibilities for biological control. After 60 years of chemical control, we are entering the ecology-based pest management era!

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Author Biography

Joop C. van Lenteren works since 1970 on behavioural ecology and population dynamics of parasitoids, theoretical and practical aspects of biological control, IPM and sustainable crop production, and anatomy and sensory physiology of parasitoid ovipositors. He is Emeritus Professor of Entomology at Wageningen University in the Netherlands. He has been and is active in various functions in the International Organization for Biological Control since 1974. His current activities include design and testing of pre-release evaluation criteria for natural enemies, development of environmental risk assessment methods, and work on access and benefit sharing in biological control.