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Abstract In augmentative biological control (ABC), invertebrate and microbial organisms are seasonally released in large numbers to reduce pests. Today it is applied on more than 30 million ha worldwide. Europe is the largest commercial market for invertebrate biological control agents, while North America has the largest sales of microbials. A strong growth in use of ABC, particularly of microbial agents, is taking place in Latin America, followed by Asia. The current popularity of ABC is due to (1) its inherent positive characteristics (healthier for farm workers and persons living in farming communities, no harvesting interval or waiting period after release of agents, sustainable as there is no development of resistance against arthropod natural enemies, no phytotoxic damage to plants, better yields and a healthier product, reduced pesticide residues [well below the legal Maximum Residue Levels (MRLs)], (2) professionalism of the biological control industry (inexpensive large scale mass production, proper quality control, efficient packaging, distribution and release methods, and availability of many (>440 species) control agents for numerous pests), (3) a number of recent successes showing how biological control can save agricultural production when pesticides fail or are not available, (4) several

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non-governmental organizations (NGOs), consumers, and retailers demanding pesticide residues far below the legal MRLs, and (5) policy developments in several regions of the world aimed at reduction and replacement of synthetic pesticides by more sustainable methods of pest management. We are convinced, however, that ABC can be applied on a much larger area than it is today. We plead in the short term for a pragmatic form of agriculture that is adaptable, non-dogmatic and combines the sustainability gain from all types of agriculture and pest management methods. We then propose to move to "conscious agriculture", which involves participation of all stakeholders in the production and consumer chain, and respects the environment and resource availability for future generations. Were "conscious agriculture" to be considered a serious alternative to conventional farming, ABC would face an even brighter future.

Keywords Augmentative biological control · Pest control policies · Benefits of biological control · Market developments in biological control · Worldwide use of biological control · Integrated pest management · Conscious agriculture

Introduction

Politicians, policy makers, retailers, consumers, growers and grower organizations are increasingly asking for and speaking about biological control. Hardly a day passes during which we, the authors of this paper, do not receive a question on how to control a certain pest, disease or weed, where to obtain biological control agents, and how to stimulate use of this environmentally safe pest management method. The European Union (EU) has been advocating the use of biological control since 2009 in its Sustainable Use of Pesticides Directive (EC 2009). The President of China recently launched a "National research program on reduction in chemical pesticides and fertilizers in China" involving more than 340 million US$, indicating a need for the development and application of non-chemical control methods. Together, the authors of this paper have been working in the field of augmentative biological control (ABC) for more than 150 years. We noted a hesitant start to ABC in the 1970s, then a burst of activity took place over the next 25 years. During the first decade of the twenty-first century fewer new biological control agents came to the market, but during the second decade we again experienced a new phase with strong growth in both the development of new agents and a market for biological control (van Lenteren 2012; Tables 1, 2 and 3 in this paper).

Simply said, biological control is the use of a population of one organism to reduce the population of another organism. Biological control has been in use for at least 2000 years, but modern use started at the end of the nineteenth century (DeBach 1964; van Lenteren and Godfray 2005). Four different types of biological control are known: natural, conservation, classical, and augmentative biological control (Eilenberg et al. 2001; Cock et al. 2010). Natural biological control is an ecosystem service (Millennium Ecosystem Assessment 2005) whereby pest organisms are reduced by naturally occurring beneficial organisms. This occurs 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. This form of biological control is currently receiving a lot of attention for pest control. Conservation biological control of plant diseases is focused on the role of the natural microbiome in suppressing plant diseases in soil and crop residues, and of the natural microbiome in and on plants in providing resilience to pest and pathogen infection (Mendes et al. 2011; Weller et al. 2002). In classical biological control, natural enemies are collected in an exploration area (usually the area of origin of the pest) and then released in areas where the pest is invasive, often resulting in permanent pest population reduction and enormous economic benefits (see Cock et al. 2010). As this was the first type of biological control deliberately and widely practiced, it is called "classical" biological control (DeBach 1964). In augmentative biological control (ABC), natural enemies (parasitoids, predators or micro-organisms) are mass-reared for release in large numbers either to obtain immediate control of pests in crops with a short production cycle (inundative biological control) or for control of pests during several generations in crops with a long production cycle (seasonal inoculative biological control) (Cock et al. 2010; Lorito et al. 2010; Parnell et al. 2016; van Lenteren 2012).

This paper is focussed on augmentative biological control (ABC). It has been applied with success for more than 100 years in several cropping systems (Gurr and Wratten 2000; Cock et al. 2010). In this paper, we illustrate (1) the important role ABC is playing today, (2) how many biological control agents are commercially available and against which pests they are applied, (3) in what way ABC can result in cleaner, greener, healthier and more sustainable agriculture through policy measures and regulations, and, finally, (4) the need for a type of agriculture that respects the environment and optimizes use of ecosystem services.

Note: in this paper we often use the word 'pest' as defined by FAO/IIPC (1997), which includes animal pests, weeds and diseases.

Where is augmentative biological control currently applied?

Large scale regular releases and mass production of natural enemies means that ABC is often a commercial activity (van Lenteren 2012). ABC is thought to have been used for the first time in China around 300 AD (van Lenteren and Godfray 2005). Modern ABC started in the 1880s with the use of the insect pathogen *Metarhizium anisopliae* by Metchnikoff in Russia for control of beetles in various crops (MacBain Cameron 1973). Today, ABC is applied in many areas of agriculture, such as fruit and vegetable crops, cereals, maize, cotton, sugarcane, soybean, grapes and many greenhouse crops (Table 1), and is often part of an

Table 1 Worldwide use of major augmentative biological control programs (after van Lenteren and Bueno 2003), with updates and supported with references when large differences in areas under control existed between 2003 and 2016

Natural enemy	Pest and crop	Area under control (in ha)
Trichogramma spp.	Lepidopteran pests in vegetables, cereals, cotton	10 million, former USSR[a]
Trichoderma spp.	Soil diseases various crops	5 million, Brazil, Europe[b]
Trichogramma spp.	Lepidopteran pests in various crops, forests	4 million, China[c]
Cotesia spp.	Sugarcane borers	3.6 million, South America, China[d]
Metarhizium anisoplae	Lepidopteran pests in sugar cane	2 million, Brazil[e]
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, South America
AgMNPV	Soybean caterpillar in soybean	1 million, Brazil
Beauvaria bassiana	Coffee berry borer in coffee, whitefly in several crops	1 million, Brazil[f]
Entomopathogenic fungi	Coffee berry borer in coffee	0.55 million, Colombia[g]
Trichogramma spp.	Lepidopteran pests in cereals and rice	0.3 million, SouthEast Asia
Trichogramma spp.	Lepidopteran pests in sugar cane and tomato	0.3 million, NorthEast Africa
Predatory mites	Spider mites in greenhouses, fruit orchards, tea and cotton	0.07 million China[h]
Trichogramma spp.	*Ostrinia nubilalis* in corn	0.05 million, Europe
Orgilus sp.	Pine shooth moth, pine plantations	0.05 million, Chile
>30 spp. of nat. enemies	Many pests in greenhouses and interior plant-scapes	0.05 million, worldwide
Egg parasitoids	Soybean stinkbugs in soybean	0.03 million, South America
Five spp. of nat. enemies	Lepidoptera, Hemiptera, spider mites in orchards	0.03 million, Europe

[a] Recent data about use of *Trichogramma* in Russia were not available

[b] Bettiol W and Pedrazzoli D, personal communication 2016

[c] Liu et al. (2014)and Wang et al. (2014)

[d] Parra JRP and Pedrazzoli D, personal communication 2016

[e] Bettiol W and Pedrazzoli D, personal communication 2016

[f] Bettiol W and Parra JRP, personal communication 2016

[g] Aristizabal et al. (2016)

[h] Yang et al. (2014)

Table 2 Additional natural enemy species to the table of van Lenteren (2012), "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[b]	Target(s)	Year of first use	Market value[a]
Adalia spp.	Coleoptera	Latin America	Aphids	1941	M
Ageniaspis citricola	Hymenoptera	Latin America	Lepidopterans	1998	M
Allotropa convexifrons	Hymenoptera	Europe	Pseudococcids	2005	S
Allotropa musae	Hymenoptera	Europe	Pseudococcids	2006	S
Amblydromalus limonicus	Acari	Europe	Thrips, whiteflies, tarsonomids	2013	L
Amblyseius aizawai	Acari	Asia	Mites	1992	M
Amblyseius longispinosus	Acari	Asia	Mites	1990	S
Amblyseius makuwa	Acari	Asia	Mites	1991	S
Amblyseius mckenziei	Acari	Europe	Mites	1985	S
Amblyseius nicholsi	Acari	Asia	Mites in citrus	1980	L
Amblyseius spp.	Acari	Australia	Mites in citrus	1990	L
Anagyrus kamali	Hymenoptera	Latin America	Pseudococcids	1990	S
Anagyrus sinope	Hymenoptera	Europe	Pseudococcids	2006	S
Anaphes nitens	Hymenoptera	Europe	Coleopterans	1995	S
Anastatus japonicus	Hymenoptera	Asia	Hemipterans	1970	L
Anastatus sp.	Hymenoptera	Asia, Australia	Hemipterans	2010	S
Anastatus tenuipes	Hymenoptera	North America	Cockroaches	1970	S
Androlaelaps casalis	Acari	Europe	Mites on vertebrates	2008	M
Anisopteromalus calandrae	Hymenoptera	Europe, North America	Coleopterans	1990	S
Aphidius sp.	Hymenoptera	Latin America	Aphids	1980	S
Billaea claripalpis	Diptera	Latin America	Lepidopterans	1976	S
Bracon brevicornis	Hymenoptera	Europe	Lepidopterans	2000	S
Cephalonomia tarsalis	Hymenoptera	Europe	Coleopterans	1995	S
Ceraeochrysa cincta	Neuroptera	Latin America	Aphids	1990	S
Ceraeochrysa smithi	Neuroptera	Latin America	Aphids	1995	S
Cheyletus eruditus	Acari	Europe	Vertebrate mites	2004	S
Chouioia cunea	Hymenoptera	Asia	Lepidopterans	2005	M
Chrysoperla asoralis	Neuroptera	Latin America	Aphids	1990	S
Chrysoperla cinta	Neuroptera	Latin America	Aphids	1990	S
Chrysoperla comanche	Neuroptera	North America	Aphids	1990	M
Chrysoperla lucasina	Neuroptera	Europe	Aphids	1995	M
Chrysoperla (=*Chrysopa*) *sinica*	Neuroptera	Asia	Aphids, lepidopterans	2000	M
Coccidophilus citricola	Coleoptera	Latin America, Europe	Diaspidids	1982	S
Coccidoxenoides peregrinus	Hymenoptera	North and Latin America	Diaspidids, pseudococcids	2006	S
Comperia merceti	Hymenoptera	North America	Cockroaches	1980	S
Copidosoma sp.	Hymenoptera	Latin America	Lepidopterans	1995	S
Cotesia marginiventris	Hymenoptera	North America	Lepidopterans	1990	S
Cotesia plutellae	Hymenoptera	North America	lepidopterans	1995	M
Cryptolaemus montrouzieri	Coleoptera	Europe, South America	Mealybugs	1927	M

Table 2 continued

Natural enemy	Classification	Region where used[b]	Target(s)	Year of first use	Market value[a]
Cycloneda limbifer	Colecoptera	Europe	Aphids	1990	S
Diachasmimorpha longicaudata	Hymenoptera	Latin America	Dipterans	1990	M
Dibrachys cavus	Hymenoptera	Europe	Dipterans	1990	S
Dirhinus giffardii	Hymenoptera	Latin America	Dipterans	1990	S
Elasmus albipennis	Hymenoptera	Europe	Lepidopterans	1995	S
Encarsia perniciosi	Hymenoptera	Europe	Scales	1932	L
Encarsia sp.	Hymenoptera	Latin America	Whiteflies	1995	S
Ephedrus cerasicola	Hymenoptera	Europe	Aphids	2008	L
Ephedrus plagiator	Hymenoptera	Europe	Aphids	2010	M
Eretmocerus hayati	Hymenoptera	Australia	Whiteflies	2006	M
Eriopsis connexa	Coleoptera	Latin America	Coccids, Aphids, hemipterans	2000	S
Eucanthecona furcellata	Hemiptera	Asia	Aphids, lepidopterans	1996	S
Euseius gallicus	Acari	Europe	Thrips, whitefly	2013	M
Euseius ovalis	Acari	Europe	Thrips, whitefly	2008	M
Euseius stipulatus	Acari	Europe, South America	Mites	2006	M
Forficula sp.	Dermaptera	Asia	Lepidopterans	2010	S
Galendromus (*Metaseiulus*) *annectens*	Acari	North America	Mites	1990	M
Galendromus (*Metaseiulus*) *helveolus*	Acari	North America	Mites	1999	S
Galendromus (*Metaseiulus*) *pyri*	Acari	North America	Mites	1995	L
Galeolaelaps gillespieii	Acari	North America	Dipterans, thrips	2010	L
Geocoris punctipes	Hemiptera	North and Latin America	Lepidopterans, whiteflies	2000	S
Gynaeseius liturivorus	Acari	Asia	Thrips, whitefly	2013	M
Habrobracon sp.	Hymenoptera	Latin America	Lepidopterans	1986	S
Haplothrips brevitubus	Thysanoptera	Asia	Thrips	2010	S
Heterorhabditis indica	Nematoda	North America	Coleopterans, dipterans	2000	S
Hydrotaea aenescens	Diptera	Europe, North America	Dipterans	2000	S
Lariophagus distinguendus	Hymenoptera	Europa	Coleopterans	1995	S
Leis (Harmonia) dimidiata	Coleoptera	Europe	Aphids	1995	S
Leminia biplagiata	Coleoptera	Asia	Aphids, whiteflies	1998	S
Leptomastix algirica	Hymenoptera	Europe	Pseudococcids	2011	S
Leptopilina heterotoma	Hymenoptera	Europe	Dipterans	2007	S
Lydella jalisco	Diptera	Latin America	Lepidopterans	1996	S
Macrocentrus prolificus	Hymenoptera	Latin America	Lepidopterans	2005	S
Mallada basalis	Neuroptera	Asia	Aphids, thrips, etc.	2000	M
Mantis religiosa	Mantodea	North America	Many pests	1970	S
Megastigmus brevivalvus	Hymenoptera	Australia	Hymenopterans	1995	S
Megastigmus trisulcus	Hymenoptera	Australia	Hymenopterans	1995	S
Menochilus sexmaculatus	Coleoptera	Asia	Aphids, whiteflies	2010	S
Metagonistylum minense	Diptera	Latin America	Lepidopterans	1980	S

Table 2 continued

Natural enemy	Classification	Region where used[b]	Target(s)	Year of first use	Market value[a]
Micromus variegatus	Neuroptera	North America	Aphids	2010	L
Necremnus artynes	Hymenoptera	Europe	Lepidopterans	2010	S
Neodryinus typhlocybae	Hymenoptera	Europe	Planthoppers	2007	S
Neoseiulus (*Amblyseius*) *barkeri*	Acari	Europe, Latin America	Thrips	1981	S
Neoseiulus longispinosus	Acari	Latin America	Mites	2005	S
Nephus quadrimaculatus	Coleoptera	Europe	Aphids, pseudococcids	2005	S
Olla abdominalis (=*v-nigrans*)	Coleoptera	North and Latin America	Aphids, hemipterans	1990	S
Orius sauteri	Hemiptera	Asia	Aphids, mites, thrips,	2005	M
Orius vicinus	Hemiptera	New Zealand	Thrips, aphids, mites	2010	M
Pentalitomastix plethoricus	Hymenoptera	North America	Lepidopterans	1980	S
Peristenus relictus	Hymenoptera	North America	Hemipterans	2001	L
Podisus sp.	Hemiptera	Latin America	Lepidopterans	1985	S
Praon sp.	Hymenoptera	Latin America	Aphids	1980	S
Propylaea japonica	Coleoptera	Asia	Aphids	2014	S
Propylaea quatuordecimpunctata	Coleoptera	Europe	Aphids	1995	S
Scymnus loewii	Coleoptera	New Zealand	Aphids	1995	S
Sphaerophoria rueppellii	Diptera	Europe	Aphids	2015	S
Stagmomantis carolina	Mantodea	North America	Many pest species	1990	S
Steinernema scapterisci	Nematoda	North America	Orthopterans	1990	S
Stethorus punctipes	Coleoptera	North America	Mites	1980	S
Stethorus sp.	Coleoptera	Latin America	Mites	1995	S
Sympherobius barberi	Neuroptera	North America	Pseudococcids, aphids, etc.	1980	L
Sympherobius maculipennis	Neuroptera	Latin America	Pseudococcids	1990	S
Sympherobius sp.	Neuroptera	Latin America	Whiteflies	1995	S
Synopeas sp.	Hymenoptera	Latin America	Dipterans	1990	S
Tamarixia radiata	Hymenoptera	Latin America	Psyllids	2010	L
Tamarixia triaozae	Hymenoptera	North and Latin America	Psyllids	2001	L
Telenomus podisi	Hymenoptera	Latin America	Hemipterans	2004	M
Telenomus sp.	Hymenoptera	Latin America	Lepidopterans	1990	S
Tenodera aridifolia sinensis	Mantodea	North America	Many pest species	1990	S
Tetrastichus hagenowi	Hymenoptera	Asia	Cockroaches	1980	S
Tetrastichus howardii	Hymenoptera	Latin America	Lepidopterans	1995	S
Thyphiodromus pyri	Acari	Latin America	Mites	2000	M
Transeius (=*Amblyseius*) *montdorensis*	Acari	Europe	Thrips, whiteflies, tarsonomids	2004	S
Trichogramma achaeae	Hymenoptera	Europe	Lepidopterans	2012	M
Trichogramma bactrae	Hymenoptera	Latin America, Asia	Lepidopterans	1980	M
Trichogramma confusum (=*chilonus*)	Hymenoptera	Asia, Australia	Lepidopterans	1970	L
Trichogramma embryophagum	Hymenoptera	Europe	Lepidopterans	1994	M
Trichogramma euproctidis	Hymenoptera	Europe	Lepidopterans	1960	M

Table 2 continued

Natural enemy	Classification	Region where used[b]	Target(s)	Year of first use	Market value[a]
Trichogramma fuentesi	Hymenoptera	Latin America	Lepidopterans	1990	S
Trichogramma japonicum	Hymenoptera	Asia	Lepidopterans	1990	S
Trissolcus basalis	Hymenoptera	Latin America	Hemipterans	1995	S
Typhlodromus occidentalis	Acari	Australia	Mites	1970	M
Wollastoniella rotunda	Hemiptera	Asia	Thrips	2005	S
Xenostigmus bifasciatus	Hymenoptera	Latin America	Aphids	2002	S
Xylocoris flavipes	Hemiptera	North America	Coleopterans	2000	S

A table listing all species used in biological control of invertebrates is provided as Supplementary electronic information

[a] Market value: *L* large (hundred thousand to millions of individuals sold per week), *M* medium (ten thousand to a hundred thousand individuals sold per week), *S* small (hundreds to a few thousands individuals sold per week) In case of doubt, when numbers sold per week could not be estimated from published material, the market value was rated as S

[b] Africa North = North of Sahara; Africa South = South of Sahara; North America = Canada + USA; Latin America = the Caribbean, Central and South America

Table 3 Registered microbial biological control agents for augmentative biological control in Australia (AUS), Brazil (BR), Canada (CA), European Union (EU), Japan (J), New Zealand (NZ) and United States of America (USA)

Microorganism[a]	Type[b] of organism	Country/region where approved	Target(s)
Adoxophyes orana GV V-0001	V	EU, J	Summer fruit tortrix
Agrobacterium radiobacter	B	NZ (1975)	Crown gall
Agrobacterium radiobacter K1026	B	USA	Crown gall
Agrobacterium radiobacter K84	B	CA, J, USA	Crown gall
Alternaria destruens 059	F	USA	*Cuscuta* spp. (dodder)
Ampelomyces quisqualis AQ10	F	EU, USA	Powdery mildew
Anagrapha falcifera NPV	V	USA	*Anagrapha falcifera*
Anticarsia gemmatalis NPV	V	BR	*Anticarsia gemmatalis*
Aspergillus flavus NRRL 21882	F	BR, USA	*Aspergillus flavus* mycotoxine
Aspergillus flavus AF36	F	USA	*Aspergillus flavus* mycotoxine
Aureobasidium pullulans DSM 14940 and DSM 14941	Y	EU, CA	Bacterial and fungal flower and foliar diseases
Autographa californica NPV	V	CA	*Autographa californica*
Bacillus amyloliquefaciens (formerly *B. subtilis*) MBI 600	B	CA, J, EU[c], NZ (2009, 2012), USA	Seed treatment, soil borne diseases
Bacillus amyloliquefaciens AH2	B	EU[c]	Fungal soil diseases
Bacillus amyloliquefaciens AT-332	B	J	*Botrytis*, powdery mildew
Bacillus amyloliquefaciens bs1b	B	NZ (2010)	Foliar diseases
Bacillus amyloliquefaciens PTA-4838	B	USA	Nematodes
Bacillus amyloliquefaciens ssp. *plantarum* (syn. *Bacillus subtilis* var. *amyloliquefaciens*) D747	B	CA, EU, J, NZ (2010)	Seedling fungal pathogens
Bacillus cereus BP01	B	USA	Foliar plant growth regulator
Bacillus firmus i-1582	B	CA, EU, NZ (2016)	Nematodes
Bacillus licheniformis SB3086	B	USA	Fungal foliar diseases
Bacillus mycoides J CX-10244	B	CA, USA	Cercospora leaf spot on sugar beet

Table 3 continued

Microorganism[a]	Type[b] of organism	Country/region where approved	Target(s)
Bacillus popilliae	B	USA	Japanese beetle
Bacillus pumilus GB34	B	USA	Root diseases of soy beans
Bacillus pumilus QST 2808	B	BR, EU, USA	Fungal foliar diseases
Bacillus subtilis ATCC 6051	B	NZ (2012)	Fungal foliar diseases
Bacillus subtilis GB03	B	CA, USA	Fungal diseases
Bacillus subtilis HAI-0404	B	J	Foliar diseases
Bacillus subtilis IAB/BS03	B	EU[c]	Foliar fungal and bacterial diseases
Bacillus subtilis KTSB	B	NZ (2008)	Foliar diseases
Bacillus subtilis QST 713	B	BR, CA, EU, J, NZ (2001), USA	Fungal foliar diseases
Bacillus subtilis var. *amyloliquefaciens* FZB24	B	CA, EU[c], USA	Fungal foliar diseases
Bacillus subtilis Y 1336	B	J	*Botrytis*, powdery mildew
Bacillus thuringiensis EG-7826	B	BR	Lepidopteran caterpillars
Bacillus thuringiensis BMP 123	B	BR	Lepidopteran caterpillars
Bacillus thuringiensis CryC encapsulated in killed *Pseudomonas fluorescens*	B	USA	Lepidopteran caterpillars
Bacillus thuringiensis CrylA(c) and CrylC in killed *Pseudomonas fluorescens*	B	USA	Lepidopteran caterpillars
Bacillus thuringiensis EG 2348	B	BR, EU	Lepidopteran caterpillars
Bacillus thuringiensis SA-11	B	BR, CA, EU	Lepidopteran caterpillars
Bacillus thuringiensis SA-12	B	BR, CA, EU	Lepidopteran caterpillars
Bacillus thuringiensis Serotype H-14	B	CA	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *aizawai*	B	CA	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *aizawai*	B	AUS (2000)	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *aizawai* ABTS-1857	B	EU, NZ (1999)	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *aizawai* NB200	B	USA	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *aizawai* GC-91	B	USA	Lepidopteran caterpillars
Bacillus thuringiensis ssp. aizawai GC-91	B	BR, EU	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *aizawai/kurstaki*	B	NZ (1995)	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *galleriae* SDS-502	B	CA	Beetles
Bacillus thuringiensis ssp. *israelensis*	B	USA	Mosquitoes
Bacillus thuringiensis ssp. *israelensis* EG2215	B	USA	Mosquitoes
Bacillus thuringiensis ssp. *israeliensis* (serotype H-14) AM65-52	B	CA, EU	Mosquitoes
Bacillus thuringiensis ssp. *kurstaki*	B	AUS (1994), BR, EU, J, NZ, USA	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* ABTS 351	B	EU	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* PB 54	B	EU	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* (ALL STRAINS)	B	CA	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* 3a,3b var SA-12	B	AUS (1996)	Cotton bollworm
Bacillus thuringiensis ssp. *kurstaki* BMP123	B	USA	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* EG	B	BR	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* EG2348	B	USA	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* EG2371	B	USA	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* EG7826	B	USA	Lepidopteran caterpillars

Table 3 continued

Microorganism[a]	Type[b] of organism	Country/region where approved	Target(s)
Bacillus thuringiensis ssp. *kurstaki* EG7841	B	USA	Lepidopteran caterpillars
Bacillus thuringiensis kurstaki evb-113-19	B	USA	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* encapsulated in killed *Pseudomonas fluorescens*	B	USA	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* h-3a,3b hd1	B	NZ (1996)	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* h-3a,3b, hd 263	B	NZ (2000)	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* h-3a,3b, SA-11	B	NZ (1995)	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* HD-1	B	AUS (2000), BR, CA	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* SA-11	B	AUS (2008)	Lepidopteran caterpillars
Bacillus thuringiensis ssp. *kurstaki* SA-12	B	AUS (2005)	Cotton bollworm
Bacillus thuringiensis ssp. *san diego* encapsulated in killed *Pseudomonas fluorescens*	B	USA	Beetles
Bacillus thuringiensis ssp. *tenebrionis* NB 176	B	CA, EU	Beetles
Beauveria bassiana 147	F	EU[c]	Red palm weevil, soft bodied insects
Beauveria bassiana 447	F	USA	Ants
Beauveria bassiana ANT-03	F	CA	Soft bodied insects
Beauveria bassiana ATCC 74040	F	EU, NZ (2013), USA	Spidermites, whitefly, thrips, aphids
Beauveria bassiana CG 716	F	BR	Whitefly, spidermites, beetles
Beauveria bassiana GHA	F	CA, EU, J	Whitefly, thrips, aphids
Beauveria bassiana HF23	F	CA	Soft bodied insects
Beauveria bassiana IBCB 66	F	BR	Whitefly, spidermites, beetles
Beauveria bassiana IMI389521	F	EU[c]	Beetles in stored grain
Beauveria bassiana k4b1	F	NZ (2005)	Thrips
Beauveria bassiana k4b3	F	NZ (2009)	Sucking insects
Beauveria bassiana NPP111B005	F	EU[c]	Banana weevil, red palm weevil
Beauveria bassiana PL63	F	Br	Whitefly, spidermites, beetles
Beauveria bassiana PPRI 5339	F	CA, EU[c]	Soft bodies insects, caterpillars
Beauveria brongniartii NBL 851	F	J	Long horn beetle etc.
Burkholderia (*Pseudomonas*) *cepacia* M54	Y	USA	Damping off diseases, nematodes
Burkholderia (*Pseudomonas*) *cepacia* J82	Y	USA	Damping off diseases, nematodes
Candida oleophila isolate I-182	Y	USA	Post-harvest fungicide
Candida oleophila O	Y	EU	Post-harvest fungicide
Chondrostereum purpureum PFC 2139	F	CA, USA	Inhibits sprouting/regrowth of shrubs and trees
Chromobacterium subtsugae PRAA4-1T	B	EU[c]	Various insects and mites
Clavibacter michiganensis ssp. *michiganensis* bacteriophage	BP	CA	*Clavibacter michiganensis* ssp. *michiganensis*
Colletotrichum gloeosporioides f. sp. *aeschynomene*	F	USA	Northern jointvetch (*Aeschynomene virginica*)
Condylorrhiza vestigialis NPV	V	BR	*Condylorrhiza vestigialis* (Braz. poplar moth)
Coniothyrium minitans CON/M/91-08	F	CA, EU, USA	*Sclerotinia* spp.
Cydia pomonella GV (Mexican strain and various other strains)	V	AUS (2010), CA, EU, NZ (1999), USA	Codling moth

Table 3 continued

Microorganism[a]	Type[b] of organism	Country/region where approved	Target(s)
Cydia pomonella GV V22 (CPGV-V22)	V	AUS (2015)	Codling moth
Erwinia carotovora CGE234	B	J	Bacterial soft rot in potato and vegetables
Fusarium sp. L13	F	EU[c]	No information found about target
Gliocladium catenulatum J1446	F	CA, EU, USA	Foliar fungal diseases
Gliocladium virens G-21	F	USA	Damping off diseases
Helicoverpa armigera NPV	V	AUS (2002), Br, EU, USA	*Helicoverpa* ssp.
Helicoverpa zea NPV	V	AUS (1999), Br, USA	*Helicoverpa* ssp.
Homona magnanima GV	V	J	Tea leaf roller, tTea *tortorix*
Isaria fumosorosea Apopka 97 (formely *Paecilomyces fumosoroseus*)	F	EU, J, USA	Soft bodied insects
Isaria fumosorosea Fe 9901	F	CA, EU	soft bodied insects
Lactobacillus casei LPT-111	B	CA	Various weeds in lawns
Lactobacillus plantarum BY	B	J	Soft rot
Lactobacillus rhamnosus LPT-21	B	CA	Various weeds in lawns
Lactococcus lactis ssp. *cremoris* M11/CSL	B	CA	Various weeds in lawns
Lactococcus lactis ssp. *lactis* LL102/CSL	B	CA	Various weeds in lawns
Lagenidium giganteum	F	USA	Mosquitoes
Lecanicillium lecanii (formerly *Verticillium lecanii*) K4V1 + K4V2	F	NZ (2012)	Thrips, whitefly, aphids, mealy bug, psyllid and passion vine hopper
Lecanicillium lecanii (formerly *Verticillium lecanii*) K4V2	F	NZ (2012)	Whitefly, thrips, aphids, passion vine hopper
Lecanicillium muscarium (formerly *Verticillium lecanii*) Ve6	F	EU, J	Whitefly, thrips
Lymantri dispar NPV	V	CA, USA	*Lymantra dispar*
Metarhizium anisopliae	F	AUS	Redheaded pasture cockchafer
Metarhizium anisopliae	F	AUS	Greyback canegrub
Metarhizium anisopliae var. *acridum*	F	AUS	Locusts
Metarhizium anisopliae ESF1	F	USA	Termites
Metarhizium anisopliae IBCB 348	F	Br	Leafhoppers
Metarhizium anisopliae PL 43	F	Br	Leafhoppers
Metarhizium anisopliae SMZ-2000	F	J	Aphids, thrips, whitefly
Metarhizium anisopliae var. *anisopliae* BIPESCO 5/F52	F	CA, EU, USA	Black vine weevil, thrips
Metschnikowia fructicola NRRL Y-27328	Y	EU[c]	Post-harvest diseases
Muscodor albus QST 20799	F	USA	Bacteria, fungi, and nematodes
Myrothecium verrucaria dried fermentation solids and solubles	F	USA	Nematodes
Neodiprion abietis NPV	V	CA	Balsam fir sawfly
Neodiprion lecontei NPV	V	CA	Redheaded pine sawfly
Nosema locustae	M	CA, USA	Grasshoppers, locusts, crickets
Orgyia pseudotsugata NPV	V	CA, USA	Ddouglas-fir tussock moth
Paecilomyces lilacinus	F	BR	Root knot nematodes
Paecilomyces lilacinus 251	F	EU	Root knot nematodes
Paecilomyces tenuipes T1	F	J	Whitefly, aphids, powdery mildew

Table 3 continued

Microorganism[a]	Type[b] of organism	Country/region where approved	Target(s)
Pantoea agglomerans C9-1	B	CA, USA	Fire blight in apples and pears
Pantoea agglomerans E325	B	CA	Fire blight in apples and pears
Pantoea agglomerans p10c	B	NZ (2006)	Fire blight in apples and pears
Pasteuria nishizawae Pn1	B	CA, EU[c], USA	Nematodes (*Heterodera*, *Globodera*)
Pepino mosaic virus CH2 isolate 1906	V	EU	Pepino mosaic virus
Pepino Mosaic Virus isolate VC 1	V	EU[c]	Pepino mosaic virus
Pepino Mosaic Virus isolate VX 1	V	EU[c]	pepino mosaic virus
Phlebiopsis gigantea (several strains)	F	EU	Root run (*Heterobasidion annosum*) in conifers
Phlebiopsis gigantea VRA 1992	F	CA	Root run (*Heterobasidion annosum*) in conifers
Phoma macrostoma	F	CA	Broadleaf weeds in turf grass
Phytophthora palmivora MWV	F	USA	Strangler vine (*Morenia orderata*)
Plodia interpunctella granulosis virus	V	USA	*Plodia interpunctella*
Pochonia chlamydosporia PC10	F	BR	Nematodes
Pseudomonas aureofaciens Tx-1	B	USA	Fungal diseases in turf grass
Pseudomonas chlororaphis 63-28	B	USA	*Pythium* spp., *Rhizoctonia solani*, *Fusarium oxysporum*
Pseudomonas chlororaphis MA342	B	EU	Seed-borne pathogens on barley and oats
Pseudomonas fluorescens G 7090	B	J	Bacterial and black rot in lettuce/cabbage
Pseudomonas fluorescens 1629RS	B	USA	Frost prevention in fruits, almond, potato, tomato
Pseudomonas fluorescens A506 (syn. 006418)	B	CA, USA	Frost prevention in fruits, almond, potato, tomato
Pseudomonas fluorescens CL145A	B	CA	Zebra mussel
Pseudomonas rhodesiae HAI-0804	B	J	Bacterial diseases in citrus, peach, plum
Pseudomonas sp. DSMZ 13134	B	EU	*Rhizoctonia solani* in potato
Pseudomonas syringae 742RS	B	USA	Frost prevention in fruits, almond, potato, tomato
Pseudomonas syringae ESC 10	B	CA, USA	Post-harvest diseases in various fruits
Pseudomonas syringae ESC-11	B	USA	Post-harvest diseases in various fruits
Pseudozyma flocculosa PF-A22 UL	F	EU[c], USA	Powdery mildew on roses and cucumbers
Puccinia thlaspeos	F	USA	*Isatis tinctoria*, dyer's woad
Purpureocilium lilacinum PL 11	F	EU[c]	Nematodes
Pythium oligandrum M1	F	EU	Fungal diseases in cereals and oil seed rape
Saccharomyces cerevisiae extract hydrolysate	Y	USA	Bacterial diseases
Saccharomyces cerevisiae LAS02	Y	EU	Fungal diseases in fruits
Sclerotinia minor IMI 3144141	F	CA	Dandelion in turf
Serratia entomophila 626	B	NZ (1994)	Grass grubs
Spodoptera exigua NPV	V	EU, USA	*Spodoptera exigua* (beet army worm)
Spodoptera frugiperda NPV 3AP2	V	USA	*Spodoptera frugiperda*

Table 3 continued

Microorganism[a]	Type[b] of organism	Country/region where approved	Target(s)
Spodoptera littoralis NPV	V	EU	*Spodoptera littoralis* (cotton leaf worm)
Streptomyces acidiscabies RL-110T	B	CA	Dandelion on turf grass
Streptomyces griseoviridis K61	B	CA, EU, USA	Fungal soil diseases in vegetables, ornamentals
Streptomyces lydicus ATCC 554456	B	NZ (2013)	Soil borne and foliar diseases
Streptomyces lydicus WYEC 108	B	CA, EU, NZ (2009), USA	Soil borne and foliar diseases
Talaromyces flavus SAY-Y-94-01	F	J	Fungal and bacterial diseases
Trichoderma asperellum (formerly *T. harzianum*) ICC012	F	EU	Fungal soil diseases in vegetables, ornamentals
Trichoderma asperellum (formerly *T.viride*) T25	F	EU	Fungal soil diseases in vegetables, ornamentals
Trichoderma asperellum (formerly *T. harzianum*) TV1	F	EU	Fungal soil diseases in vegetables, ornamentals
Trichoderma asperellum SF 04 (URM) 5911	F	BR	Damping off, *Sclerotinia sclerotiorum*
Trichoderma asperellum T211	F	BR	Damping off, *Sclerotinia sclerotiorum*
Trichoderma asperellum T34	F	CA, EU	Fungal soil diseases in vegetables, ornamentals
Trichoderma atroviridae SKT-1	F	J	Bacterial seedling blight and grain rot, seedling fungal blight
Trichoderma atroviride (5 strains)	F	NZ (1991)	Wound pathogens
Trichoderma atroviride (formerly *T. harzianum*) IMI 206040	F	EU	Fungal soil diseases in vegetables, ornamentals
Trichoderma atroviride (formerly *T. harzianum*) T11	F	EU	Fungal soil diseases in vegetables, ornamentals
Trichoderma atroviride ag1, ag2, ag3, ag5, ag11, ag15	F	NZ (1987)	Wound pathogens
Trichoderma atroviride I-1237	F	EU	Wound pathogens and fungal soil diseases
Trichoderma atroviride lu132	F	NZ (2004)	Foliar diseases
Trichoderma atroviride SC1	F	EU	Wound pathogens
Trichoderma gamsii (formerly *T. viride*) ICC080	F	EU	Fungal soil diseases in vegetables, ornamentals
Trichoderma hamatum TH382	F	USA	Fungal soil diseases in vegetables, ornamentals
Trichoderma harzianum	F	AUS (2004)	Eutypa dieback in grapes
Trichoderma harzianum KRL-AG2 (syn. T22)	F	CA, EU, USA	Fungal soil diseases in vegetables, ornamentals
Trichoderma harzianum ESALQ-1306	F	BR	Damping off, *Sclerotinia sclerotiorum*
Trichoderma harzianum IBL F006	F	BR	Damping off, *Sclerotinia sclerotiorum*
Trichoderma harzianum ITEM 908	F	EU	Soil borne diseases
Trichoderma harzianum T-39	F	USA	Fungal soil diseases in vegetables, ornamentals
Trichoderma polysporum ATCC 20475	F	USA	Wound pathogens
Trichoderma polysporum IMI 206039	F	EU	*Botrytis cinerea*, *Chondrostereum purpureum*
Trichoderma stromaticum CEPLAC 3550	F	BR	Witch's broom

Table 3 continued

Microorganism[a]	Type[b] of organism	Country/region where approved	Target(s)
Trichoderma virens G-41	F	CA	Fungal soil diseases in vegetables, ornamentals
Trichoderma viride ATCC 20476	F	USA	Wound pathogens
Typhula phacorrhiza 94671	F	CA	Snow molds in turf
Ulocladium oudemansii U3	F	NZ (2004)	Foliar diseases, *Pseudomonas syringae*
Verticillium albo-atrum (formerly *V. dahliae*) WCS850	F	CA, EU, USA	Dutch elm disease
Xanthomonas campestris pv. *vesicatoria* bacteriophage	BP	USA	*Xanthomonas campestris* pv. *vesicatoria*

Information obtained from (AUS) https://portal.apvma.gov.au/pubcris, (BR) http://extranet.agricultura.gov.br/agrofit_cons/principal_agrofit_cons, (CA) http://pr-rp.hc-sc.gc.ca/ls-re/result-eng.php?p_search_label, (EU) http://ec.europa.eu/food/plant/pesticides/eu-pesticides-database/public/?event=homepage&language=EN, (J) Japan Plant Protection Association, (NZ) https://eatsafe.nzfsa.govt.nz/web/public/acvm-register, (USA) https://iaspub.epa.gov/apex/pesticides/f?p=chemicalsearch:1

[a] Strain numbers if available

[b] *B* bacterium, *BP* bacteriophage, *F* fungus, *Y* yeast, *V* virus

[c] Pending in the EU

Integrated Pest Management (IPM) program that provides an environmentally and economically sound alternative to chemical pest control (van Lenteren and Bueno 2003; Cock et al. 2010). Increasingly, seed treatments with microbial biological control agents are also used as a form of ABC (Abuamsha et al. 2011). We estimate that in 2015 ABC was applied on more than 30 million ha worldwide (Table 1).

Since the 1970s, ABC has moved from a cottage industry to professional research and production facilities, as a result of which many efficient agents have been identified, quality control protocols, mass production, shipment and release methods matured, and adequate guidance for farmers has been developed (van Lenteren 2003, 2012; Cock et al. 2010; Ravensberg 2011). In this paper we will not describe the process of collection, evaluation, development of mass production and registration of biological control agents in detail. Information concerning these factors for invertebrate biological control agents can be found in Cock et al. (2010) and for microbial biological control agents in Köhl et al. (2011), Ravensberg (2011) and Parnell et al. (2016). When searching for natural enemies, it is not unusual to find dozens or more species attacking a certain pest, but criteria such as population growth rate, host range, and adaptation to crop and climate can often be used to quickly eliminate clearly inefficient species. The most promising species are compared by using characteristics such as efficacy of pest control, potential environmental risks and economy of mass rearing. For the screening of microbial control agents, large collections of hundreds or thousands of isolates are typically established and high throughput screening assays are increasingly applied to assess important traits such as cold tolerance, metabolite production and efficacy against the target pest.

Important recent successes in the use of ABC include the virtually complete replacement of chemical pesticides by predators (mites and hemipterans) to control thrips and whiteflies on sweet peppers in greenhouses in Spain (Calvo et al. 2012), and hemipteran predators to control new invasive pests like the South American pinworm *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) (Urbaneja et al. 2012). These examples show how well biological control with invertebrate biological control agents can function in modern agriculture, and that they can actually save agriculture in large areas that otherwise would have had to terminate vegetable production. Another recent success deals with the importance of microbial control agents. The invasion of the cotton bollworm, *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae), into Brazil in 2012 caused tremendous damage to corn, cotton, and soy, as pesticides were not effective due to resistance, or were simply not available. Emergency approvals of the entomopathogenic bacterium *Bacillus thuringiensis* and baculovirus products provided farmers with the only effective control method at the time (Pratissoli et al. 2015).

Europe is still the largest commercial market for ABC with invertebrate biological control agents, which is partly due to political support of biological control within IPM programs (EC 2009), but also due to consumer demand, pressure by NGOs (e.g., Greenpeace 2007) and a well-functioning, highly developed biological control industry. The next largest market is North America, followed by Asia, Latin America, Africa and the Middle East. A strong growth of ABC with arthropods is taking place in Latin America and the same is expected to occur in Asia (Dunham 2015; ResearchandMarkets 2016b). According to the latest marketing reports (e.g., ResearchandMarkets 2016a) North America is now the largest market for biopesticides, followed by Europe.

Commercially available biological control agents

Cock et al. (2010) mentioned 170 species of invertebrate biological control agents that have been used in ABC in Europe. Van Lenteren (2012) provided a list of about 230 species of invertebrate biological control agents that have been used in pest management worldwide, but recognised that this list was not yet complete. Collection of new data in 2016 showed the use of almost 350 natural enemy species (Table in Supplementary electronic information). There are about 500 commercial producers of invertebrate biological control agents worldwide, although most of these employ less than ten people each. Less than ten producers employ more than 50 staff, with the largest producer having about 1400 employees. In addition to commercial producers, there are hundreds of government-owned production units, particularly in China, India and Latin America. Also, and especially in Latin America, some large-scale farmers and growers are involved in producing their own natural enemies. In addition to the species listed in Table 2, invertebrates are commercially produced for biological control of weeds (40 species), for soil improvement (six species), as feed and food (40 species), and as pollinators (ten species). These species are not listed in Table 2.

After predators and parasitoids, microbial biological control agents are the next most commonly used organisms in ABC. As far as we are aware, Table 3 may be the first list published about microbial biological control agents registered worldwide. Although we realize the list is not yet complete, it provides information on about 209 microbial strains from 94 different species commercially available for control of pests. Information we could obtain on registered strains was not always consistent. In some cases agents seem registered without strain information or under different strain identifications for different regions, so that some organisms may be listed more than once in Table 3. Microbial biological control agents are produced by approximately 200 manufacturers, but this is an underestimate as no data are available for China or India (Dunham 2015). There is a great diversity of manufacturers and often they are specialised in one or two types of microorganisms and production methods. The majority of manufacturers are small to medium-sized companies. Recently, large multinational agro-chemical companies are getting involved in the production and marketing of so-called biopesticides, again through the acquisition of small to medium-sized companies. New companies are still founded on a regular basis, and acquisitions and mergers occur frequently. There is a similar trend to consolidation as that which occurred in the seed and chemical pesticides business in the past decades.

Viability of commercial biological control market

Producers of natural enemies are understandably reluctant to provide data about market developments, profit margins and sales volumes. In 2015, the global pesticide market had a value of US$ 58.46 billion (ResearchandMarkets 2016a). The global market of biological control agents (invertebrates and microorganisms) was approximately US$ 1.7 billion in 2015 (Dunham 2015; Dunham W, personal communication 2016), which is less than 2% of the pesticide market. Growth of the market for synthetic pesticides is expected to be between 5 and 6% over the next five years (Research and Markets 2016b), but interestingly, growth of the biological control market has been faster: it showed an annual increase of sales of 10% before 2005 and more than 15% per year since 2005 (Dunham 2015; Dunham W, personal communication

2016). The largest European biological control companies are still getting the main part of their income from sales of invertebrate biological control agents, but the contribution of microbial biological control agents is steadily increasing. Commercial ABC is used in protected crops (e.g., vegetables, ornamentals) and high-value outdoor crops (e.g., strawberries, vineyards), contributing to about 80% of the market value of invertebrate biological control agents. Biological control programs for each of these crops may involve up to 15–20 different species of natural enemies (van Lenteren 2000). The remaining 20% of the market value for natural enemies comes from application of relatively simple, cheap but effective biological control programs often using only one biological control agent (e.g., *Trichogramma* spp. against lepidopterans in cereals and sugarcane, and *Cotesia* spp. against lepidopterans in sugarcane). Almost 40% of the income of the European companies originates from invertebrate biological control agents sold for control of thrips, another 30% for control of whitefly, 12% for control of spider mites, 8% for control of aphids, and the remaining 10% for control of various other pests (Bolckmans K, personal communication 2016). Since 2005, predatory mites have contributed enormously to the growth of the market for invertebrate biological control agents as a result of: the (re)discovery of their use for control of whiteflies (Nomikou et al. 2001), finding more efficient species for thrips control (Messelink et al. 2006), the development of techniques to enhance dispersal and establishment of predatory mites in crops (Messelink et al. 2014), and the development of new highly economic production technologies (Bolckmans et al. 2005).

The recent increase in annual market growth for biological control agents is the result of many factors. Compared with synthetic chemical pesticides, ABC agents show important inherent positive characteristics: they are less detrimental to the health of farm workers and persons living in farming communities; they do not have a harvesting interval or re-entry period as do pesticides; they are more sustainable, as there has been no development of resistance against arthropod ABC agents; they do not cause phytotoxic damage to plants and, as a result, most farmers report better yields and healthier crops after switching to biocontrol-based IPM. Increasingly, produce in Europe and North America can only be sold when residue levels are well below the legal MRLs because of retailers demands. In some cases low residue levels give farmers a preferred partnership with retailers who prefer to buy products with less residues. Furthermore, biological control might contribute to considerable reduction in emission of greenhouse gasses in comparison with pesticide use (Heimpel et al. 2013).

In addition to these inherent advantages of biological control, consumers have and will increasingly express concerns about food safety and environmental impact issues in relation to synthetic pesticide use, though they often have no direct way to influence crop protection policies. However, food retailers and supermarkets cleverly exploit this and use these two concerns increasingly in advertising their produce. In many countries, retailers and supermarkets more strongly restrict use of pesticides than do government policies (Buurma et al. 2012), and, particularly in Europe, the effect of NGOs reporting on excess residue levels and illegal use of pesticides has had a positive effect on the use of biological control (e.g., Greenpeace 2007). Adoption of IPM programs in the EU, in which biological control is a cornerstone, has increased interest in and application of ABC (Lamichhane et al. 2017). Concurrently with the adoption of this IPM approach, it was announced that a large number of pesticides were to be legally discontinued and this has also led to requests for ABC solutions. Policy measures such as a strong reduction in use of synthetic pesticides in China have also opened avenues for ABC. A number of other national measures have been shown to stimulate use of ABCs. Examples are fast track and priority registration of low risk pest control agents such as ABC’s similar to the special registration procedure for biopesticides in the USA (EPA 2017), subsidizing biological control agents to growers (several countries in the EU) and application of pesticide levies (e.g., Denmark).

However, ABC, and biological control in general, also face a very serious problem. Pests have been accidentally exported for many years, but at an ever increasing rate (Bacon et al. 2012). Until recently, potential biological control agents could be collected in the country of origin of the pest, evaluated, mass produced and released when an effective agent was found. But today, under the Convention on Biological Diversity (CBD 1993) countries have sovereign rights over their genetic resources and agreements governing the access to these resources and the sharing of benefits arising from their use need to be established between involved parties [i.e., Access and Benefit Sharing (ABS) (Cock et al. 2010)]. This means that currently, permission to sample potential biological control agents can only be granted by the country that has sovereign rights over the genetic resources and collection of new natural enemies has become increasingly difficult or impossible in countries which have first accidentally exported the pest, a situation which seems very unreasonable.

What might boost future use of ABC?

First, we expect that the above-mentioned factors that are responsible for the recent growth of ABC will play an even more important role in the near future, as their influence will spread to other countries and regions worldwide due to support for "greener" agriculture by consumers, NGOs, governments and growers. Another influential issue accelerating use of ABC relates to changing regulations. Regulations should facilitate the use of innovative sustainable solutions resulting in a choice for the ecological best pest control option. This can be realized by fast track registration, priority registration, and use of a combination of comparative assessment of pest control methods together with the substitution principle, through which an environmentally safer pest control method can substitute for a synthetic pesticide (EC 2009). Also zonal authorization (e.g., authorization for all of the EU instead of registration per country), permanent registration (instead of reregistration after 10–15 years) and mutual recognition of registration by member states in the EU are all measures that are likely to result in increased application of microbial biological control, and are now considered for low risk substances including ABC's in the EU. The changes in registration procedures will result in faster registration of more microbial biological control agents and, logically, in lower product costs. The Environmental Protection Agency (EPA) in the USA is already applying several of the above-mentioned factors related to registration of ABC's, but the EU is slow in adopting specific criteria and procedures for biological control agents. Development of a specific protocol for registration of microbial biological control agents that will be used locally or worldwide, would be another big step forward in making use of biological control more attractive and accessible for farmers.

Removal of pesticides from the market due to observed health, non-target and environmental effects (e.g., the recent development concerning neonicotinoids; EASAC 2015), the development of resistance that makes pesticides less effective, and the appearance of new pests for which no pesticides are available (e.g., *Tuta absoluta* invasion in Europe in 2006, Urbaneja et al. 2012) all stimulate use of ABC. Non-governmental organizations (NGOs) have in several cases successfully used information about environmental effects and illegal use of pesticides to initiate a change from chemical to biological control [e.g., in 2005 in the Almeria region in Spain, chemical control of pests in sweet pepper was replaced by biological control in a period of two years (Calvo et al. 2012)]. A very fast change from chemical control to biological control as in sweet peppers in Spain also occurred for other crops in that region. In the 1980s there was a similar drastic change from chemical to biological control in vegetable production in Northwest Europe (van Lenteren 2000), though this was not caused by a pesticide scandal like the one concerning sweet pepper production in Spain (Greenpeace 2007), but by growers recognition of the inherent positive characteristics of biological control mentioned above, and by resistance of several insect pests to conventional chemical pesticides. The development of new and better biological control solutions, improved and more stable formulations for microbial biological control agents and their use as seed treatments, more convenient application methods for invertebrate biological control agents (equipment to release biological control agents in crops, use of drones, etc.) and increasingly stable formulations of microbial biological control agents, have also contributed to growth in uptake of biological control. Interestingly, growers quickly took up the extra knowledge and methods to make biological control a success, and in quite a number of cases came up with new insights and technologies to improve release and establishment of invertebrate biological control agents. They also stimulated researchers and the biological control industry to provide new invertebrate biological control agents for emerging pests. We hope farmer's organizations will create a new renaissance in crop protection by seeing the many positive sides, including economics, of ABC. In their own interest they should become much more proactive and demand priority and fast track registration of innovative sustainable control methods.

Finally, application of the "true cost" principle for chemical pesticides would strongly increase the market for biological control. Pesticides are subsidized by governments because the industry is not held responsible for human illnesses and deaths as a result of chronic exposure to pesticides, and also does not have to provide the funding to repair damage done to the environment (e.g., reduction of biodiversity, limiting or even preventing the functioning of ecosystem services such as pest and disease control, pollination and cleaning of (drinking) water). Thus, pesticide costs related to harmful effects on human health and the environment are externalized and are actually paid by society, which is unethical and unscrupulous because the pesticide industry only reaps the economic benefits without being responsible for these costs. Benefit-cost ratios of chemical pesticides are usually said to be in the order of 4 when these "external hidden" costs are not taken into account (e.g., Pimentel and Burgess 2014). If true costs were applied to pesticides their benefit-cost ratio would still in most cases be higher than 1, in other cases close to 1, and in some cases even below 1, and, according to Bourguet and Guillemaud (2016) "the profitability of pesticides has, indeed, been overestimated in the past." Realistic pricing involving true costs would result in much higher costs of chemical pesticides and fairer competition with non-chemical alternative controls. Although hidden costs of pesticides have been documented since the 1980s, they have seldom resulted in an increase of pesticide prices. A first step to true cost pricing would be to apply levies on synthetic pesticides resulting both in higher, thus more realistic pricing, as well as in fairer competition with prices of biological control agents used in IPM programs.

And what next?

Too often the following reasoning is used to justify the use of synthetic pesticides: agriculture has to feed some ten billion people by the year 2050, so we need to strongly increase food production, which can only be achieved with usage of synthetic pesticides. This reasoning is simplistic, erroneous and misleading. Simplistic because it ignores a multitude of other approaches to pest, disease and weed control that we summarize below under IPM, erroneous as sufficient healthy food can be produced without synthetic pesticides (e.g., IPES-Food 2016; Ponisio et al. 2014; UN 2017), and misleading in that it minimizes the importance of a well-functioning biosphere and high biodiversity for the long-term sustainable production of healthy food for a growing human population (De Vivo et al. 2016; Erisman et al. 2016; IPES-Food 2016; Tillman et al. 2012). This short-sighted mercenary attitude might actually result in very serious environmental problems in the near future (e.g., van Bavel 2016). A more sensible approach to food production is to ask ourselves: (1) how can we create a healthy and well-functioning biosphere in which biodiversity is treasured instead of strongly reduced, both because of its necessity for sustainable food production and maintaining a hospitable biosphere for humans (utilitarian approach), as well as because of our ethical responsibility (ethical approach), (2) how can healthy food best be produced in this well-functioning biosphere, and (3) what kind of pest, disease and weed management fits in such a production system.

From the time agriculture developed some 10,000 years ago until only 65 years ago, agriculture was, after periods with slash and burn activities, an holistic activity, based on a systems approach. Farming societies had to design plant production and crop protection programs based on prevention of pests. This true form of IPM included, among others, planning of crop combinations, crop rotation, tillage, use of resistant or tolerant crop cultivars, choice of the right planting and harvesting periods, biological, mechanical and physical control etc. (e.g., Ehler 2006). Due to an understanding of plant genetics, the development of synthetic fertilizers and pesticides, agricultural research changed from an holistic approach to an extremely reductionist science where pests are avoided by a prophylactic approach consisting of calendar sprays or by curative treatments. A total systems approach to agriculture no longer seemed necessary, but this is a short-sighted and dangerous viewpoint and the ever increasing use of synthetic pesticides has resulted in a serious loss of biodiversity (e.g., EASAC 2015), which in turn resulted in prevention or reduction in functioning of the ecosystem services of pest reduction, pollination and water purification (Millennium Ecosystem Assessment 2005). A prophylactic approach is also an exorbitant input of resources with financial consequences of billions of US$ (Costanza et al. 1997; Pimentel and Burgess 2014; Bourguet and Guillemaud 2016).

Lewis et al. (1997) made a plea to return to a system approach based on true IPM. True IPM is a durable, environmentally and economically justifiable system in which pest damage is prevented through the use of natural factors limiting pest population growth, and only—if needed—supplemented with other, preferably non-chemical measures (Gruys, P. in van Lenteren 1993). As stated above, there are many alternatives for synthetic pesticides, and cultural methods together with modern plant breeding and biological control within true IPM programs have been shown to provide excellent yields (e.g., Radcliffe et al. 2009). The fact that more creativity, knowledge and ecological insight are needed to be able to apply such pesticide-free crop management schemes should no longer be an excuse to use unsustainable, environmentally unsafe and toxic synthetic pesticide programs (UN 2017). We are not advocating a dogmatic, one-sided pest control approach, and we also do not support a static holistic approach in which (agro-) ecosystems are seen as non-changing functional units. Instead we propose to combine the sustainability gain from all types of agriculture and pest prevention/control methods, and consider agro-ecosystems as constantly changing systems. In such an approach, we are convinced that ABC can be applied much more than it is today, but we also know it will not solve all pest problems. A seriously neglected form of biological control, conservation biological control, should be the basis of most crop protection programs by providing sufficient invertebrate biological control agents and undisturbed buffering microbiomes in soils and plants when pests invade an agro-ecosystem (Gruys 1982; Blommers 1994; Berendsen et al. 2012). Delaying or preventing sprays will result in the reduction of secondary pests that arise after killing natural enemies of pest organisms. These often cause resurgence problems when synthetic pesticides are used. Host-plant resistance is one of the important cornerstones of IPM and should play a more important role in pest prevention. In IPM we are not dependent on full resistance, often partial host-plant resistance is enough because pest populations develop more slowly and natural enemies can more easily reduce such populations. Both classic and modern plant breeding, including CRISPR-Cas and RNAi, will help us design robust IPM programs. In order to obtain more governmental and public support, we—researchers and practitioners of biological control—will have to collaborate with all stakeholders in pest management to involve them and make them aware of the important economic, environmental, societal and environmental benefits of biological control. Recent experiences in New Zealand, where farmers pushed for and implemented biological control (Hardwick et al. 2016), protected crops in South-eastern Spain (growers and public embraced biological control: Jacas and Urbaneja 2009) and weed control in South Africa (public supported weed biological control in the working for water program: Moran et al. 2005) shows that widely disseminated information about successes of biological control projects result in strong public support and increased government funding.

In conclusion, we see the urgent need for a new type of agriculture that is somewhere between conventional and organic, is flexible and non-dogmatic. We might address it as Conscious Agriculture, a term which we borrowed from the conscious capitalism movement (Mackey and Sissodia 2014). Conscious agriculture involves participation of all stakeholders in the production and consumption chain, and respects the environment and resource availability for future generations. This is in contrast with conventional agriculture which concentrates on profit maximization and externalizing the cost of the harmful effects on human health, society and the environment (Robinson 2007; Erisman et al. 2016). Conscious agriculture fits seamlessly into a “common agricultural and food policy” as recently published in a position paper by Fresco and Poppe (2016). They review societal challenges and options for innovation, and conclude that such a policy should not concentrate on agriculture only, but needs to be developed with participation of all stakeholders, and will help “the entire food chain—from farm to fork, from animal breeding to human food production—to cope with the challenges of the coming decades”. Within conscious agriculture, the first line of crop protection consists of strictly enforced quarantine regulations, prevention of pest development by cultural methods, host-plant resistance, classical and conservation biological control, preventative releases of natural enemies (an aspect of ABC) and use of banker plants to establish natural enemy populations before pests establish (Messelink et al. 2014). When pests exceed acceptable population levels, i.e. when economic damage is expected to occur, augmentative biological control should be the first option for pest management, if needed in combination with other IPM tactics. Were "conscious agriculture" to be considered a serious alternative to conventional farming, augmentative biological control would face an even brighter future.

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