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Review

Latin America has the largest area under augmentative biological control worldwide, mainly with applications in open field crops[☆]

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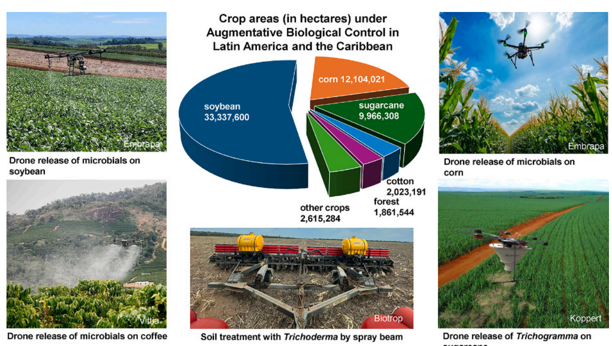
HIGHLIGHTS

- Use of augmentative biocontrol dramatically increased recently in Latin America.
- Was applied on >62 million hectares in 2024 and used mainly in open field crops.
- Is in the majority of cases based on the use of microbial control agents.
- Is often not aimed on development of resilient systems.
- Is for a large part used in fodder crops and less so in food crops.

GRAPHICAL ABSTRACT



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ABSTRACT

During the past 30 years, augmentative biological control (ABC) has received increasing interest and is now applied in a large diversity of crops on many hectares in Latin America and the Caribbean. Around the year 2000 4.35 million hectares were estimated to be treated with ABC, in 2018 this had grown to 31.4 million hectares, and the estimate for 2024 was about 62 million hectares. Many factors explain this dramatic increase, the most important being (a) the development of microbial agents that are relatively cheap compared to macrobial agents, easy to produce, store and apply, and reliable, (b) the fine tuning and drastic shortening of registration procedures, (c) a change in attitude towards use of alternatives for chemical pesticides among young farmers. However, there are also factors frustrating implementation of ABC of which the most important are the lobbying activities of the synthetic pesticide industry and lack of application of the true cost principle for these pesticides which makes them unrealistically cheap. Major differences with other world regions are that in Latin America ABC is almost exclusively applied in the open field, is often not based on development of resilient systems and changed in the 21st century from mainly using macrobial control agents to increased applications with microbial control agents.

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1. Introduction

Biological control (biocontrol) is, simply said, the use of a living organism (predator, parasitoid, antagonist or pathogen) to reduce the population density or to mitigate the effect of another organism (pest, disease agent or weed). Thus, like Stenberg et al. (2021), we do not consider pheromones, plant-based pesticides, toxins produced by organisms, natural products and growth stimulants to be biocontrol agents as the pest and disease control industry tends to do (see e.g. CropLife, 2025), but biologically-based control methods. The main reasons to exclude biologically-based control methods from the definition of biocontrol are that the exploration, collection and evaluation phase of biocontrol agents is very different from the other approaches and these agents also have a completely other mode of action than the other pest control methods. One of the consequences of using this definition of biocontrol is that hundreds and thousands of hectares treated with only the toxin of *Bacillus thuringiensis* Berliner (Caryophanales: Bacillaceae) and not the bacteria itself are not included in the estimates of areas under biocontrol in this paper.

Augmentative biocontrol (ABC) is the production and release of native or exotic biocontrol agents to obtain direct pest control and has been applied since the early 1900 s in Latin America and the Caribbean (van Lenteren et al., 2020; 2021a), though quantitative data about the areas under ABC have been lacking until recently. A summary on the information about different types of biocontrol used in this region up to 2019 based on data found in Hagen and Franz (1973); van Lenteren and Bueno (2003) and van Lenteren et al. (2020) is presented in Table 1. Data for the first two periods are not reliable and certainly underestimates.

Natural biocontrol (NBC) is an ecosystem service whereby the damage of pest organisms is mitigated by naturally occurring beneficial organisms, was hardly studied or documented, but certainly has always played a role on vast areas and in many crops. Also, conservation biocontrol (ConsBC), whereby farmers try to protect and stimulate the performance of naturally occurring natural enemies, was used since the early 1900 s as we learned when we collected information for the book "Biological Control ~~in~~ Latin America and the Caribbean: Its Rich History and Bright Future" (van Lenteren et al., 2020).

Information about classical biocontrol (CBC), consisting of the introduction of an exotic natural enemy from a pest's area of origin, to control a pest in an area where it has invaded, was always quite well documented concerning crops, pests and natural enemies used, but not about areas treated up to the year 2000. The data for the last period were obtained by contacting many researchers in Latin America and the Caribbean, by studying the literature (English, Spanish and Portuguese) and by internet searches. Even so, data for NBC are very incomplete, but it was important to see that researchers in many countries now realize the value of NBC and try to establish the role of naturally occurring antagonists, pathogens, predators and parasitoids. We believe that data for areas under ConsBC are underestimated as well, though it is currently getting increased attention, especially through changes in cropping systems such as no-till and crop-livestock-forestry systems. The estimated areas under CBC and ABC are most reliable and based on these data it can be concluded that the Latin American region had the largest areas under these types of biological control in the year 2020 when compared with other world regions (see e.g. Mason, 2021; van Lenteren et al., 2021b).

Table 1
Use of different forms of biocontrol and hectares under biocontrol in Latin America and the Caribbean up to and including 2018 (adapted from van Lenteren et al., 2020).

Period	Hectares (ha) under different forms of biocontrol and number of countries using a certain type of biological control			
	Classical (CBC) ha/# countries	Augmentative (ABC) ha/# countries	Conservation (ConsBC) ha/# countries	Natural (NBC) ha/# countries
1895 – 1969	? / 16	? / 4		
1970 – 1999	? / 16	4,350,000 / 17		
2000 – 2018	30,747,889 / 29	31,381,131 / 27	447,114 / 13	2,001,846 / 19

adapted from van Lenteren et al., 2020).

Below, we will show that application of augmentative biological control currently is growing very fast in Latin America, with a main role of microbial pest and disease control. However, first we will shortly summarize the development of augmentative biological in this region. Arthropod pests seem to have not occurred frequently in pre-hispanic agriculture, though locusts *Schistocerca piceifrons* Walker (Orthoptera: Acrididae), grasshoppers and larvae of Lepidoptera and Coleoptera were said to cause outbreaks every now and then, and affect, among others, maize, potato, bean, cassava, and sweet potato, and also mosquitoes and lice were considered harmful arthropods (Granados, 2011; Mejía, 1993; Melic, 2003). That serious damage caused by arthropod pest was not common during this period might be explained by a combination of the use of inter- and multi-cropping, lack of large monocrops, cultural practices such as crop rotation, change of cropping sites and using periods of fallow. Importantly, most arthropods were considered not to cause damage, and were categorized as food, medicine or part of nature without "being good or bad". Farmers recognized, among others, spiders, nymphs of Odonata and lizards as natural enemies of arthropods. In addition, farmers tolerated arthropod injury to crops since they grew crops to support their family and not to produce food to maximize their income. Castillo (2020) mentions that "ancient people recognized the value and richness of insects as natural enemies of pests …". During the colonial period in Latin America, there are records of the first attempts to control the locust *S. piceifrons* by cultural methods like tillaging, burning fields, crop rotation, hand removal of adults and egg sacs, and by "praying" (Hilje and Saunders, 2008).

The first documented use of ABC concerns releases of the native predatory mite *Pyemotes ventricosus* (Newport) (Trombidiformes: Phyemotidae) against the Mexican cotton boll weevil, *Anthonomus grandis* (Boheman) (Coleoptera: Curculionidae) in 1904 (Arredondo-Bernal and Rodríguez-Vélez, 2020). The earliest use of a microbial agent in ABC in this region consists of the importation and field application of the entomopathogenic bacterium *Coccobacillus acridiorum* D'Herelle for augmentative biological control of the locusts *Schistocerca cancellate* (Serville) (Orthoptera: Acrididae) in 1911 in Uruguay (Basso et al., 2020), in 1913 in Colombia (Kondo et al., 2020) and in 1915 in Costa Rica (Blanco-Metzler and Morera-Montoya, 2020). Thus, interestingly, microbial agents were used early in the history of ABC in Latin America, which also happened in Europe where the first modern use of ABC concerned mass production and field application of *Metarhizium anisopliae* (Metchnikoff) Sorokin (Hypocreales: Clavicipitaceae) for control of beetles in various crops (MacBain Cameron, 1973). The first use of ABC with a parasitoid occurred in 1915 in Trinidad and Tobago, where the parasitoid *Anagrus urichi* Pickles (Hymenoptera: Mymaridae) was used for the control of froghoppers *Aeneolamia varia saccharina* (Dist.) (Homoptera: Cercopidae) (Khan and Isaac, 2020). Later, Latin America pioneered in development and use of entomopathogenic nematodes with Argentina, Brazil, Chile, Cuba and Venezuela as major foci of activity (San-Blas et al., 2019). Initially, in the 1950 s, exotic species such as *Steinernema carpocapsae* Weiser (Rhabditida: Steinernematidae) were introduced to control white grubs, *Diloboderus abderus* Sturm (Coleoptera: Scarabaeidae), but this was soon followed by the discovery of a large number of native species which were tested for control of many different pest species (San-Blas et al., 2019). However, ABC only became a really important strategy in addition to large scale use of classical biological control around the 1970 s with the mass production (van Lenteren and Bueno, 2020a) and release of the *Cotesia flavipes* (Cameron) (Hymenoptera: Braconidae) on thousands of hectares of sugarcane to control the sugarcane borer *Diatraea saccharalis* (Fabricius) (Lepidoptera: Crambidae) in several Latin American countries.

Currently, when areas under biocontrol are considered, the conclusion is that microbial control agents (bacteria, fungi and viruses) are used at a larger scale than macrobial control agents (invertebrates such as arthropod predators and parasitoids, and nematodes) in Latin America. Microbial control agents not only play an important role in the control of arthropods, but also in the control of plant diseases and the most important case concerns application of *Trichoderma* spp. (Hypocreaceae) to control soil-borne diseases caused by plant pathogenic fungi on millions of hectares, among others in Brazil (Bueno et al., 2020; de Medeiros and Bettiol, 2023).

In this paper the current situation of use of ABC will be illustrated. As the editors of this special issue wrote in their invitation letter to authors, ABC is often applied in protected cultivation, but we will make clear in this chapter that this type of biocontrol also works very well and on vast areas in the open field. Although, there are countries in this region that have extensive greenhouse areas under biocontrol (e.g. Colombia, Ecuador and Mexico), the majority of ABC takes place in the field. In this respect, the Latin American region might differ significantly from other world areas. We will present the most recent developments, show in which areas this region has particularly interesting ABC projects, discuss factors limiting and stimulating biocontrol and speculate about the future of biocontrol in Latin America and the Caribbean.

2. Material and methods

The data collected for ABC published in van Lenteren et al. (2020; 2021a) formed the basis for this publication. Next, authors of the country specific chapters in these books were contacted and asked for updates of the data. Additionally, we searched the literature and internet sites for information about recent ABC programmes.

3. Results

Re-analysis of old data, information obtained from scientists we contacted, from internet and the scientific literature resulted in the data provided in Table 2. The table does not specify details about projects, scientific names of crops, pests, diseases and biocontrol agents, instead we refer to van Lenteren et al. (2020; 2021a) for these details. For species and products used in ABC programmes and registered in Argentina, Bolivia, Brazil, Chile, Paraguay and Uruguay up to 2022, we refer to Cosave (2022). Table 2 shows that ABC is used widely in the region, but is still limited or not used in some countries (e.g. Barbados, Belize, Dominica, El Salvador, French Guyana and islands, Guatemala, Haiti, Jamaica, Puerto Rico, several other Caribbean Islands, and Suriname). If information indicating growth of ABC in the countries with limited or no use of ABC was not found, they will not be discussed below, though information about testing or limited use of ABC can be found in Table 2.

3.1. ABC situation in Latin American and Caribbean countries

Argentina has been working on ABC projects since long, but is better known for extensive use of CBC. Currently, ABC is used on substantial areas of citrus, sugarcane, fruit and nut orchards, in vineyards and in pine plantations (Greco et al., 2020). In forestry, most biocontrol projects start with a CBC approach, but when CBC does not result in complete control, regular ABC releases of biocontrol agents are made to increase control. Since 2018, the areas treated with microbial control agents developed fast, but use of parasitoids and predators is still dominant.

Bolivia has large areas under ABC in sugarcane, citrus, potato, coffee, quinoa and soybean. The country aims to become less dependent on chemical pesticides, stimulates development of organic production and has specific programmes for the development of microbial control

Table 2
Areas under augmentative biocontrol in Latin America and the Caribbean in hectares (van Lenteren et al., 2020 and updates).

Country /Main pests/crops/control agent	Area under ABC in ha	Source
Argentina		
Diaphorina citri in **citrus** by macrobials	1,250	1
Pests in **cotton, corn** and other **field crops** by microbials	+(?)	2
Pests in **fruit and nut orchards** by microbials	4,100	3
Pests in **horticulture** by macrobials	65	4
Sirex noctilio in **pine** by macrobials	> 62,000	5, Andorno et al. (2022)
Diatraea saccharalis in **sugarcane** by macrobials	25,000	6
Pests in **vineyards** by microbials	8,600	7
Weeds in **water** by macrobials	150	8
Pests in **poultry farms** by macrobials	+(?)	9
Barbados		
Pink bollworm in **cotton** by macrobials	+ (?)	van Lenteren and Colmenarez (2020)
Lepidopterans in **vegetables** by macrobials	part of 600	idem
Pink hibiscus mealybug in **various crops** by macrobials	+ (?)	idem
Belize		
Froghoppers in **sugarcane** by microbials	experimental	Sosa et al. (2020)
Bolivia		
Sugarcane spittlebug in **sugarcane** by macrobials	150,000	Franco et al. (2020)
Sugarcane borers in **sugarcane** by macrobials	4,500	idem
Fruit flies in **citrus** by macrobials	54,000	idem
Potato tuber moths in **potato** by microbials	1,800	idem
Potato weevils in **potato** by microbials	180,000	idem
Coffee berry borer in **coffee** by macrobials and microbials	23,000	idem
Lepidopterans in **quinoa** by macrobials and microbials	23,000	idem
Hemipterans and lepidopterans in **soybean** by macrobials and microbials	470,000	idem
Brazil		
Pests in **apple** orchards by macrobials	1,800	10
Banana weevil in **banana** by microbials	21,340	11
Pest and diseases in **coffee** by microbials	344,460	11
Pests and diseases in **corn** by microbials and macrobials	12,013,340	11
Pests and diseases in **cotton** by microbials and macrobials	1,845,640	11, 12, Bueno et al. (2020)
Five insect pests in **eucalyptus** plantations by macrobials	100,000	13
Leafminer in **melon** by macrobial	12,000	14
Wood wasp in **pine** plantations by macrobials	1,500,000	13
Pests and diseases in **soybean** by microbials and macrobials	32,557,100	11, 14
Pests and diseases in **sugarcane** by microbials and macrobials	7,188,180	11, 14
South American tomato leafminer in **tomato** by macrobials	12,000	14
Pests in **various crops** by macrobials	500,000	14, Bueno et al. (2020)

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Table 2 (*continued*)

Country /Main pests/crops/control agent	Area under ABC in ha	Source
Spider mites, gall midges in **vegetables and fruits** by macrobials	15,000	10, Bueno et al. (2020)
Asian citrus psyllid in **citrus**	+(?)	14
Ceratittis, Anastrepha fruit flies in **fruit**	+ (?)	Bueno et al. (2020)
Mate tree borer in **mate**	+(?)	idem
Soil-borne diseases and nematodes in **various crops**	+ (?)	idem
Chile		
Weevils in **berries, hazelnut and truffle-boring trees** by macrobils & microbials	915	15
Pests in plantation **forests** by macrobials	> 32,000	16
Diseases in **fruit** and vegetables by microbials	24,657	Barra-Bucarei et al. (2020)
Coccinellids in **various crops** by microbials	4,472	idem
Lepidopterans in **various crops** by macrobials	2,500	idem
Tuta absoluta in **vegetables** by macrobials	20	idem
Colombia		
Pests in **coffee** by macrobials	1,500	17, Kondo et al. (2020)
Pests in **citrus** by macrobials	1,500	idem
Pests in **horticulture and ornamentals** by macrobials	12,000	idem
Pests in **fruit** by macrobials	46,500	idem
Pests in **oil palm** by macrobials	5,000	idem
Pests in **rice** by macrobials	48,000	idem
Pests in **sugarcane** by macrobials	245,896	idem
Coffee berry borer in **coffee**	+ (?)	idem
Black sikatoga disease in **banana**	+ (?)	idem
Grey mold in **blackberry**	+ (?)	idem
Cassava hornworm in **cassava**	+ (?)	idem
Insect pests in **common bean** and **soybean**	+ (?)	idem
Insect pests in **corn**	+ (?)	idem
Insect pests in **cotton**	+ (?)	idem
Mosquito vectors of **human** diseases	+ (?)	idem
Lace bug in **oil palm**	+ (?)	idem
Lance flies **in passion fruit**	+ (?)	idem
Lepidopteran and aphid in **pine**	+ (?)	idem
Insect pests and soil-borne diseases in **potato**	+ (?)	idem
Flies in **poultry** and **livestock**	+ (?)	idem
Insect pests and diseases in **vegetables** and **ornamentals**	+ (?)	idem
Costa Rica		
Cashew nut borer in **cashew** by macrobials	70	Blanco-Metzler et al. (2020)
Asian citrus psyllid in **citrus** by macrobials	6,000	idem
Coffee berry borer in **coffee** by microbials	4,000	idem
Dipterans and mealybugs in **pineapple** by macrobials	780	idem
Sugarcane borers, spittlebugs in **sugarcane** by macrobials and microbials	4,800	idem
Banana root borer, banana mealybug in **banana** by microbials	+ (?)	idem
Fruit flies in various **fruit** by macrobials	+ (?)	idem
Cuba		
Sugarcane borer in **sugarcane** by parasitoids	1,600,000	Márquez et al. (2020)
Cylas formicarius in **sweet potato** by macrobials	1,618	idem
Vars lepidopterans in **various crops** by macrobials	283,252	idem
Various pests in **various crops** by microbials	276,470	idem
Soil-borne diseases in **various crops** by microbials	60,032	idem
Dominica	0	
Dominican Republic		
Cassava hornworm in **cassava** by macrobials	1,070	Serra and van Lenteren (2020)
Citrus root weevil in **citrus** by macrobials and microbials	> 1,400	idem
Coffee berry borer in **coffee** by microbials	62,500	idem
Melon worm moth in **melon** by macrobials	> 500	idem
Rice stem stink bug in **rice** by macrobials	174,389	idem
Sugarcane borer in **sugarcane** by macrobials	114,742	idem
Lepidopterans in **tomato** by macrobials	> 543	idem
Various pests in **vegetables** by macrobials	250	idem
Banana root borer in **banana**	+ (testing)	idem
Ecuador		
Pests and diseases in **banana** by microbials	15,160	Castillo et al. (2020)
Frosty pod rot in **cacao** by microbials	1,224	idem
Coffee berry borer in **coffee** by microbials	10,000	idem
Soil-dwelling diseases in **fruit** by microbials	115	idem
Pests and diseases in **mango** by microbials	1,400	idem
Pests and diseases in **oil palm** by microbials	5,125	idem
Pests and diseases in **ornamentals** by microbials and macrobials	2,612	idem
Diseases in **palmito palm** by microbials	400	idem
Soil-borne disease in **papaya** by microbials	160	idem
Pests and diseases in **pineapple** by microbials	300	idem
Lepidopterans in **rice** by microbials	360	idem
Rice blast disease in **rice** by microbials	360	idem
Sugarcane borers in **sugarcane** by macrobials	40,000	idem
Pests and diseases in **vegetables** by microbials and macrobials	397	idem
Stalk borers in **maize**	+ (?)	idem
Fall armyworm in **maize and soybean**	+ (?)	idem
Sugarcane leafhopper in **sugarcane**	+ (?)	idem
Spider mites in **various crops**	+ (?)	idem
El Salvador		
Leaf hoppers in **cotton** by microbials	+ (?)	van Lenteren (2020a)
Nematodes in **horticulture** and **fruit** by microbials	+ (?)	idem
Mosquitos in **lakes** by macrobials	+ (?)	idem
Soil diseases in **various crops** by microbials	+ (?)	idem
Lepidopterans and coleopterans in **various crops** by microbials	+ (?)	idem

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Table 2 (*continued*)

Country /Main pests/crops/control agent	Area under ABC in ha	Source
French Guiana, Guadeloupe and Martinique		
Pests in **vegetables** by macrobials	+ (?)	Ryckewaert & Vayssières (2020)
Guatemala		
Coffee berry borer in **coffee** by macrobials	100	van Lenteren (2020b)
White grub in **corn** by macrobials	20	idem
Lepidopterans in **cotton** and vegetables by microbials	3,600	idem
Cotton leafworm in **cotton** by macrobials	14,000	idem
Diamondback moth in **crucifers** by macrobials	100	idem
Sugarcane borer in **sugarcane** by macrobials and microbials	156	idem
Guyana		
Palm castaniid in **palm** by microbials	12,000	van Lenteren (2020c)
Red palm mite in **palm** by macrobials and microbials	+ (testing)	idem
Haiti	0	
Honduras		
Pests in **citrus, corn, ornamentals and vegetables** by macrobials	299	Trabanino et al. (2020)
Disease in **coffee** by microbials	500	idem
Whitefly in **sweet potato and vegetables** by microbials	1,000	idem
Arthropod pests in **various crops** by microbials and macrobials	21,000	idem
Diseases in **various crops** by microbials	8,000	idem
Nematode pests in **various crops** by microbials	1,000	idem
Cattle tick in **cattle** by microbials	+ (testing)	idem
Jamaica		
Five pests in **citrus** by macrobials	7,846	Sherwood and van Lenteren (2020)
Coffee berry borer in **coffee** by macrobials and microbials	+(?)	
Mexico		
Five pests in **citrus** by macrobials and microbials	76,849	Arredondo-Bernal and Rodríguez-Vélez (2020)
Fruit flies in various **fruit** by macrobials	10,685	idem
Vine mealybug in **grape** by macrobials	28,365	idem
Two pests in **sorghum** by macrobials and microbials	82,094	idem
Soybean caterpillar in **soybean** by microbials	10,000	idem
Vars pests in **sugarcane** by macrobials and microbials	276,608	idem
Locusts and grasshoppers in **various crops** by microbials	20,000	idem
Various pests in **vegetables** by macrobials in open field	35,355	idem
Various pests in **vegetables/ ornamentals** by macrobial in greenhouses	>29,000	idem
Water hyacinth in **water** by macrobials	1,516	idem
Coffee berry borer in **coffee**	+ (?)	idem
Mexican cotton boll weevil in **cotton**	+ (?)	idem
Common flies in **urban areas/ livestock**	+ (?)	idem
Mosquito larvae in **water**	+ (?)	idem
Giant reed in **water**	+ (?)	idem
Nicaragua		
Coffee berry borer in **coffee** by microbials	70	Castillo (2020)
Fall armyworm in **corn** by microbials	21	idem
Various pests in **horticultural crops** by macrobials	323	idem
Black sheath rot in **rice** by microbials	4,000	Trabanino et al. (2020)
Pests in **sugarcane** by microbials	10,000	Castillo (2020)
Diseases in **vegetables** by phytopathogenic fungus	70	idem
Panama		
Diamondback moth in **cabbages** by macrobials	1	Zachrisson and Barba (2020)
Sugarcane borers in **sugarcane** by macrobials	38,629	idem
Leaf miners in **horticultural crops**	+ (?)	idem
Paraguay		
Diseases and pests in **soybean** by microbials	300,000	11
Sugarcane borer in **sugarcane** by macrobials	+ (?)	Antúnez et al. (2020)
Pests and diseases in several crops by microbials	+ (?)	idem
Peru		
Aphids and lepidopterans in **alfalfa** by macrobials	4,669	Mujica and Whu (2020)
Pests and diseases in **asparagus** by macrobials and microbials	42,715	idem
Pests and diseases in **avocado** by macrobials and microbials	45,100	idem
Pest and diseases in **blueberry** by macrobials and microbials	381	idem
Pests in **citrus** by macrobials and microbials	7,639	idem
Coffee berry borer in **coffee** by microbials	222	idem
Lepidopterans and aphids in **corn** by macrobials	3,841	idem
Aphids and budworm in **cotton** by macrobials	146,000	idem
Pests and diseases in **fruit** by macrobials and microbials	276	idem
Pests and diseases in **grapevine** by macrobials and microbials	2,036	idem
Pests in **olive** by macrobials	1,784	idem
Pests and diseases in **pepper** by macrobials and microbials	1,224	idem
Pests and diseases in **pomegranate** by macrobials and microbials	1,707	idem
Leaf miners in **potato** by microbials	76	idem
Pests and diseases in **quinoa** by macrobials and microbials	183	idem
Sugarcane borer in **rice** by macrobials	211	idem
Pests and diseases in **sugarcane** by macrobials and microbials	215,130	idem
Aphids in **tara fruit** by macrobials	5,113	idem
Pests and diseases in **tomato** by macrobials and microbials	814	idem
Pests and diseases in **various vegetables** by macrobials and microbials	937	idem
Puerto Rico		
Coffee berry borer in **coffee** by macrobials	+ (?)	Ramos et al. (2020)

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Table 2 (*continued*)

Country /Main pests/crops/control agent	Area under ABC in ha	Source
Remaining Caribbean Islands		
Sugarcane froghopper in **sugarcane** by microbials	+ (?)	van Lenteren and Bueno (2020b)
Suriname		
Various pests in **vegetables** by macrobials	0.5	van Sauers-Muller and Jagroup (2020)
Mites in **citrus**	+ (?)	idem
Trinidad and Tobagp		
Pests in **citrus** by macrobials	2,000	Khan and Isaac (2020)
Pests in **sugarcane** by macrobials and microbials	15,000	idem
Pests in **vegetables** by macrobials and microbials	350	idem
Uruguay		
Lepidopterans in **apple** by microbials	60	18
Psyllids in **citrus** by macrobials	260	18
Weevils in **eucalyptus** plantations by macrobials	20	Basso et al. (2020)
Various pests in **horticultural crops** by macrobials and microbials	290	18
Sirex in pine plantations by macrobials	145,000	19
Lepidopterans in **soybean** by macrobials	500	18
Venezuela		
Sugarcane borers and froghoppers in **sugarcane** by macrobials	35,867	20
Lepidopterans in **various crops**, e.g. **corn** by macrobials	> 855	20
Lepidopteran pests in **cotton, sorghum and tobacco** by macrobials	+ (?)	Vásquez et al. (2020)
Plant diseases in **various crops** by microbials	+ (?)	20

Notes: macrobials = evertebrate natural enemies (parasites, parasitoids and predators), microbials = micro-organisms (viruses, bacteria and fungi); +? = ABC applied but area unknown, 1. A. Aguirre, INTA, Argentina (pers. comm. 2024), 2. A.V.Toledo, CINDEFI, Argentina, (pers. comm. 2024), 3. D. Hervé, SENASA, Argentina, L. Cichón, S. Garrido & G. Quintana, INTA, Argentina (pers. comm. 2024), 4. L. Valles, Brometán SRL, Argentina (pers. comm. 2024), 5. A.V. Andorno, INTA, Argentina (pers. comm. 2024), 6. M.G. Luna & N. Greco, CEPAVE, Argentina, (pers. comm. 2024), 7. B. Marcucci, INTA, Argentina (pers. comm. 2024), 8. G. Cabrera Walsh, FUEDEI, Argentina (pers. comm. 2024), 9. M. Zapater, Insectarios SRL, Argentina and M.F. Cingolani, CEPAVE, Argentina (pers. comm. 2024), 10. V.H.P.Bueno, UFLA, Brazil (pers. comm. 2024), 11. W. Bettiol, Embrapa, Brazil (pers. comm. 2024), 12. R.P. de Almeida, Embrapa, Brazil (pers. comm. 2024), 13. L.R. Barbosa, Embrapa, Brazil (pers. comm. 2024), 14. J.R.P. Parra, ESALQ/USP, Brazil (pers. comm. 2024), 15. L.D. Devotto Moreno, INIA, Chile (pers. comm. 2024), 16. S.A. Estay, Univ. Austral de Chile, Chile (pers. comm. 2024), 17. T. Kondo, Agrosavia, Colombia (pers. comm. 2024), 18. C. Basso, Univ. de la Republica, Uruguay (pers. comm. 2024), G. Martinez, INIA, Uruguay (pers. comm. 2024), 20. F. Ferrer, Venezuela (pers. comm. 2024).

agents. This country also intensively studies the role of NBC and integrates ABC in NBC programmes, particularly in quinoa and soybean (Franco et al., 2020).

Brazil, which occupies almost half of the South American continent, has vast areas with monocrops that, due to the warm climate, allow for two or three harvests annually on the same fields. As a result, Brazil is a major agricultural power, and produces more than 33 % of the world's soybean, sugarcane and coffee (Agrianual, 2022). Contrary to many other Latin American countries, Brazil is mainly known for very large-scale application of ABC, although it also has several large CBC projects which are described in Bueno et al. (2020). Particularly interesting examples of early ABC projects applied extensively are (1) the on-farm production of AgMNPVvirus by a simple *in vivo* method for control of the soybean caterpillar *Anticarsia gemmatalis* Hubner (Lepidoptera: Noctuidae) on more than 2,000,000 ha of soybean during the 1980 s and 1990 s (Moscardi, 1999), (2) 4,000,000 ha of sugarcane with *M. anisopliae* for control *Mahanarva frimbriolata* (Stal) (Hemiptera: Cercopidae), (3) 5,500,000 ha of soybean with *Trichoderma* spp. for control soilborne diseases (Bueno et al., 2020), and (4) 3,500,000 ha of sugarcane with labour intensive mass produced *Cotesia flavipes* Cameron (Hymenoptera: Braconidae) parasitoids to control *Diatraea saccharalis* F. (Lepidoptera: Crambidae) (Macedo, 2000; see the *Cotesia* mass production scheme in van Lenteren and Bueno, 2020a).

Recently, the use of ABC increased enormously mainly because of a new method for registering biocontrol agents for use in organic agriculture (de Medeiros and Bettiol, 2023). Facilitating registration made it easier, quicker and cheaper to register agents. Another measure was to prioritize registration of biological agents and to register these agents per target (the pest) and not per crop like is done for chemical pesticides. Registration of a biocontrol agent in Brazil takes only about 2 years, while it takes up to 10 years in Europe. The result is that the harvested area under ABC with registered biocontrol agents in Brazil increased from about 22 million hectares in 2018 (Bueno et al., 2020) to more than 56 million hectares in 2024 (Table 2 and de Medeiros and Bettiol, 2023). Currently, there are more than 600 biocontrol products registered in Brazil (Agrofit, 2025). Next to using registered product, Brazil is since long known for on-farm production of agents, varying from small scale activities to large scale production similar to that of companies having biocontrol agents as their core business. Estimates are that on-farm production is responsible for about 14 % of the biocontrol market (de Medeiros and Bettiol, 2023, Fischer et al., 2023) and applied on an area of 12,007,000 ha in 2024.

Interestingly, the Ministry of Agriculture in Brazil recently elected 10 priority pests and diseases for registration of biocontrol agents with the effect that companies used a fast-track procedure to reach this target. Now, at least one biocontrol agent is already available for each important plant disease (de Medeiros and Bettiol, 2023). The largest recent market growth for biocontrol is related to control of nematodes, this now represents more than 40 % of sales of biocontrol agents and substituted the chemical nematicide market in soybean, corn, sugarcane and cotton. The results obtained with nematode biocontrol raised the awareness of farmers about the role biocontrol could play in the control of other soil-borne plant pests.

Chile has millions of hectares under CBC, but only a relatively small area under ABC and mainly for control of diseases in fruit and vegetables, for control of lepidopterans in various crops and for weevils in orchards and berry fields. An important source for ABC is the "Chilean Collection of Microbial Genetic Resources" with thousands of accessions and many of these have potential as phytopathogenic, nematophagous and entomopathogenic fungi (Barra-Bucarei et al., 2020). Chile has large areas with pine and eucalyptus plantations, where CBC with parasitoids is successfully used, but occasionally or regularly this needs to be supported by ABC through releases of parasitoids or entomopathogenic nematodes (Estay, 2020).

Contrary to many other Latin American countries, *Colombia* is, like Brazil, and Cuba, better known for ABC than for CBC. ABC projects concern control of aphids, thrips, spider mites, whiteflies and lepidopterans on an extensive area of ornamentals and vegetables grown in greenhouses and the ABC programmes are similar to those used in European greenhouses. ABC is also extensively applied in open field crops like cassava, citrus, coffee, cotton, corn, potato, rice, sugarcane and sorghum, and in forest plantations (palm for oil and pine), but information about areas under ABC are often not available. Both macro- and microbial agents are used in ABC, and an overview of biocontrol agents and companies / organizations producing these control agents is presented in Kondo et al. (2020).

Although one of the smaller countries in Latin America, *Costa Rica* is having a number of interesting ABC programmes because of investments in the development of sustainable agriculture particularly as a result of the demand for residue free export products. The majority of exporting companies of fruit, flowers, cotton, and coffee have implemented IPM practices, and have laboratories and trained professionals for production and use of entomopathogens, parasitoids and predators (Blanco-Metzler and Morera-Montoya, 2020). Currently, many biocontrol projects are being carried out to support development and production of entomopathogenic fungi by small providers.

Development and application of ABC is since long high on the agenda of the government of *Cuba*. The country has a network of more than 200 "Centers of Reproduction of Entomophagous and Entomopathogens" where large amounts of insect pathogenic fungi and bacteria, as well as parasitoids are produced. A National Program for Biological Control is managed by the Plant Health Service and involves 14 provincial laboratories that provide certified strains and ecotypes of biocontrol agents, gives advice about production, and carries out quality control of products. There is also a state extension network advising farmers how to use biocontrol agents as well as monitor their efficacy once they are applied to crops (Márquez et al., 2020).

The *Dominican Republic* has considerable areas of open field crops with coffee, rice and sugarcane under ABC, partly based on use of native natural enemies and microbial agents found on the island during large scale prospecting programmes (Serra and van Lenteren, 2020). Like in several other Latin American countries, the use of biocontrol within IPM programmes is stimulated by demands of foreign importers of products free of synthetic pesticide residues. The Dominican Republic is one of the leading exporters of tropical organic products like coffee, banana and other fruit, cocoa, which are using, among others, biocontrol agents for pest and disease control.

Most ABC programmes in *Ecuador* are based on use of microbial agents against pests and diseases in various crops. Parasitoids and predators are used in sugarcane, ornamentals and vegetables. During the past 60 years, the National Institute for Agriculture Research (INIAP), has given special importance to research and training in biocontrol to ensure the well-being of farmers and consumers, and to protect the environment. The institute also conducts inventories of native beneficial insects and the Ministry of Agriculture (MAGAP) helps to establish laboratories for the production of biocontrol agents. Also, several commercial producers of biocontrol agents are active on the ABC market (Castillo et al., 2020).

The largest ABC programme in *Guatemala* concerns control of cotton leafworm with *Trichogramma* parasitoids and *Chrysopa* predators.

Guyana is well known for the discovery in 1932 and first time use of the dipteran parasitoid *Lydella* (*Metagonistylum) minense* Tns (Diptera: Tachinidae) for control of the sugarcane borer, *D. saccharalis* (van Lenteren, 2020c). This parasitoid was later introduced to many other Latin American countries and is applied in CBC and ABC programmes. The largest ABC programme in Guyana is that of the palm castniid *Lapaeumides* (=*Eupalamides*) *dedalus* (Cram.) (Lepidoptera: Castniidae) in palm plantations by a native bacterium species.

Almost all ABC in *Honduras* takes place with applications of microbial control agents, mainly with entomopathogenic fungi. The start of biological control in this country was initiated by the creation of a "Center for Biological Control", now the "Biological Control Laboratory", in 1989 of the Plant Protection Department (Departamento de Protección Vegetal, DPV) of the Escuela Agrícola Panamericana in Zamorano (Trabanino et al., 2020). Students and staff of this Center made inventories of natural enemies and microbial control agents of many of aquatic weeds and of the crops grown in Honduras. Since 2000 the Biological Control Laboratory produces microbial agents and registered them in several neighbouring countries.

Jamaica has a remarkably large number of successful NBC programmes, partly in combination with CBC (Sherwood and van Lenteren, 2020). ABC is mainly applied in citrus.

In the period from 1900 − 1970 many programmes in *Mexico* concerned CBC, often based on successes obtained abroad and in most cases with parasitoids. ABC is currently popular and applied for control of aphids, thrips, leaf miners, mites and whiteflies in vegetables and ornamentals, where several species of predators, parasitoids and microbial agents are used, for control of sugarcane borers with parasitoids, of sugarcane aphids with predators in soybean, pests in citrus with parasitoids and predators and of several species of locusts and grasshoppers with an entomopathogenic fungus. Sixty-five companies produce 40 species of natural enemies and contrary to many other Latin American countries, Mexico authorizes the import and application of a large number of arthropod species produced outside Mexico (Arredondo-Bernal and Rodríguez-Vélez, 2020). Mexico, one of the larger Latin American countries, is remarkable (1) for still mainly using macrobial control agents and only has a limited area treated with microbials, and (2) for having a large greenhouse industry with ABC programmes similar to those used in Europe.

In *Nicaragua*, biocontrol started relatively late (end of the 1950 s), but thanks to the efforts of international and government institutions, NGOs, private companies and universities the country now produces 12 biocontrol agents, with sugarcane having the largest area under ABC.

The main ABC programme in *Panama* is biocontrol of the sugarcane borer with parasitoids. In addition, a lot of research is done to develop biocontrol of pests in rice.

Paraguay has large projects on sampling for parasitoids, predators and microbial agents of important pests in crops like cotton, corn, bean, peanut, sesame, soybean and sugarcane, and during the past decades many of the found organisms have been identified (Antúnez et al., 2020). Information about areas under ABC are difficult to obtain for crops produced in relatively small organic fields. A large area of soybean is under ABC in Paraguay with similar biocontrol agents as used in Brazil.

In *Peru*, the Ministry of Agriculture already created a "Center for Introduction and Rearing of Useful Insects (CICIU)" for biocontrol of the most economically important pests in the 1960 s. In the 1990 s, a National Program for Biological Control was created to intensify biocontrol in important crops through training of professionals, and promotion and sale of biocontrol agents to farmers. Biocontrol agents were supplied to different agricultural valleys via a network of production laboratories, which reared 42 species of biocontrol agents to control pests in more than 45 crops, resulting in a strong increase of application of ABC (Mujica and Whu, 2020). Currently, the sub-direction of Biological Control (SCB) of CICIU, now part of the National Service of Agrarian Health (SENASA) has laboratories to produce 35 species of parasitoids and predators, 2 species of entomopathogenic nematodes and many strains of microbiological control agents for pest and disease control. Large agro-exporting and agro-industrial companies (sugarcane, asparagus, avocado, citrus and olive plantations) have a high demand for biocontrol agents in order to obtain pesticide residue free produce, and SENASA now grants "Green Farm Certification" to farms producing products free of pesticides, where biocontrol agents are used for pest and disease control after inspection and/or evaluation visits.

Related to biocontrol, *Trinidad and Tobago* is best known for its Commonwealth Institute of Biological Control (CIBC and later CAB International) research unit from which after a period of quarantine and cleaning of import shipments, many parasitoids and predators were sent to many Caribbean Islands and to countries of the Latin American continent. This activity is ongoing and mainly concerns CBC (Khan and Isaac, 2020). ABC is applied on a considerable area of sugarcane and citrus.

Uruguay has a long history of successful CBC projects, initiated mass production laboratories for the production of entomopathogens and macrobial control agents used in ABC as of the 1980 s and also is actively surveying for and evaluating native natural enemies and microbial control agents (Basso and Cibils, 2020). The largest area under ABC concerns pine plantations where *Sirex noctilio* Fabricius (Hymenoptera: Siricidae) is controlled by releases of the nematode *Deladenus siricidicola* (Bedding) (Nematoda: Neotylenchidae) usually imported from Chile and occasionally from Brazil (Martínez, 2020; Gonzalo Martinez, pers. comm. 2024).

In *Venezuela* ABC is mainly used in sugarcane where releases of dipteran and hymenopteran parasitoids are released for control of sugarcane borers and froghoppers since the 1950 s. About 20 years ago, the Venezuelan government organized a network of biocontrol laboratories producing natural enemies and microbial agents to promote agroecological approaches to sustainable crop production (Vásquez et al., 2020). As a result of this network, ABC is now applied in crops such as sugarcane, potato, bell pepper, tomato, and corn.

3.2. Crops and areas under ABC in Latin America and the Caribbean

The areas under ABC in Latin American countries are summarized in Table 3. Problems related to the reliability of the estimates given in Table 3 are mentioned in the section Preamble of the Discussion. The total area under ABC is at least 62 million hectares, so a doubling of the area we estimated for 2018 (van Lenteren et al., 2020). Most of this increase is the result of the enormous surge in application of microbial control agents in Brazil in monocropping systems of soybean, corn, sugarcane and cotton, and can be explained by the factors stimulating ABC mentioned below. The five countries with the largest areas under ABC from high to low are Brazil (> 56 million ha), Cuba (> 2 million), Bolivia (almost 1 million), Mexico (> 0.5 million ha) and Peru (almost 0.5 million ha) (Fig. 1).

Ranking countries by area under ABC is not the fairest way to indicate their biocontrol activities and, therefore, van Lenteren and Cock (2020) ranked them relative to the size of the country and number of inhabitants. In this paper, we ranked them relative to the total area of agriculture land including tree plantations grown for wood or timber (FAO, 2023). Using the amount of ABC per unit of agricultural land as indicator, the sequence of the countries with most ABC is Cuba, Trinidad and Tobago, Brazil, Bolivia and Dominican Republic (Fig. 2). This ranking shows some obvious differences with the one presented in Fig. 1. Cuba has the largest area of agricultural land under ABC, which is the result of long-term research efforts for all types of biocontrol due to limited availability of chemical pesticides. Bolivia keeps its high position, but Mexico and Peru are replaced by Trinidad and Tobago and the Dominican Republic. Trinidad and Tobago has obtained this high position as result of a long and intensive research investment in biocontrol due to the presence of a CABI research station. The Dominican Republic has invested a lot in research and extension during the past 50 years.

Most ABC is applied in soybean, corn, sugarcane, cotton and forest plantations and together these crops account for more than 96 % of the total area under ABC (Fig. 3). These crops are not primarily grown to produce basic food for local consumers. The majority of soybean and corn is used as fodder for cattle and poultry, sugarcane to produce sugar and alcohol, cotton for production of fabric and wood for making paper or used to make furniture and for building purposes. Less than 4 % of ABC is applied on food crops.

The use of microbial control agents has increased dramatically over the past three decades in this region and most of this increase took place in soybean crops (Fig. 4).

However, the use of micro- and macrobial control agents largely differs per country (Fig. 5). In Brazil, the country with the largest area under ABC, microbials dominate, but macrobials are still applied on the largest area in Cuba, Bolivia, Mexico and Peru. In countries with relatively small areas under ABC the same can be observed: some countries – Guyana, Honduras, Nicaragua and Paraguay – mainly use microbials, while in other countries – Argentina, Colombia, Costa Rica, Dominican Republic, Guatemala, Jamaica, Panama, Uruguay and Venezuela – use of macrobials still dominates.

4. Discussion

4.1. Preamble

Obtaining data for areas under biocontrol and evaluation of the reliability of the data is a time-consuming affair. We tried to double check data by contacting more than one source. This was possible for some countries (e.g. Argentina, Brazil, Chile, Uruguay and Venezuela), but for quite a number of countries we could not obtain reliable updates for the 2018 data published by van Lenteren et al. (2020). Often, the use of biocontrol was only expressed in monetary value and in many cases the biocontrol industry was reluctant to provide data, maybe understandable because of competition issues. A recent problem, now that part of the biocontrol industry joined lobby groups like CropLife (see e.g. CropLifeBrasil, 2020), is that data about application of true biocontrol (see first paragraph of introduction of this paper) are often difficult to identify among the use of many different types of bio-inputs.

Another problem is how various sources express the areas under biocontrol. Data were easiest to analyse for (semi-)permanent crops like forest plantations and fruit and citrus orchards, where we could take the crop area treated with ABC as value for the area under ABC. It was more difficult for crops with two or more harvests per year for which we received data of the cumulative area treated with ABC (e.g. soybean and corn harvested twice per year in Brazil, and, thus, the area planted with these crops is two times the land area used for production of soybean, and ABC data are also twice the land area planted). In these cases, we used the cumulative area treated with ABC. In still other cases, the area under ABC was expressed as the number of times a certain ABC agents was applied multiplied by the crop area (e.g. when a biocontrol agents was applied 10 times on an area of 500,000 ha, the area under biocontrol was expressed as 10 x 500,000 = 5 million ha). In such cases, we considered the area planted as the area under biocontrol.

Still another problem is the use of different products – e.g. a microbial agent for disease control and a parasitoid for control of a pest - in the same crop. Like van Lenteren and Cock (2020), when calculating total areas under ABC it was attempted to minimize overestimates by checking if pests and diseases in a certain crop were under control of more than one type of biocontrol agent. In these cases, the largest area under ABC for a certain type of biocontrol agent was taken as the estimate.

The areas under ABC presented in Table 3 are often underestimates. For various countries and crops it is known that ABC is used but areas on which applied are not known, which can be seen in Table 2 where many projects for Brazil, Colombia, Dominican Republic, El Salvador and Mexico are listed with "+ (?)" in the column for the areas treated. Still, the current data with all the limitations mentioned above do show that ABC is applied on vast surfaces in Latin America and is growing fast.

Finally, the areas under ABC for crops in Table 3 mean that on that surface one or more augmentative biocontrol agents are used for control of pests, diseases or weeds often within an IPM programme, and does not exclude the use of other, non-biocontrol methods for the control of additional injurious organisms. Examples are soybean and corn, where frequent applications of synthetic herbicides are common.

4.2. Factors stimulating use of ABC

Many factors influence the decision to use ABC. In this section we first mention a number of straightforward, but important criteria for Latin American growers to use this type of biocontrol. The criteria are based on a total of 145 years of work in biocontrol by the authors, including many meetings with various stakeholders (e.g. farmers, growers, producers of natural enemies, extension specialists, employees of regulation authorities and ministries of agriculture) during this period. While studying new solutions for ABC, we had regular meetings with directors, heads of research and field workers of some of the largest biocontrol industries to identify factors increasing the probability of

Table 3
Areas under augmentative biocontrol in 2024 per country and crop in Latin America and the Caribbean in hectares (data from Table 2).

Crop → Country↓	Soybean	Sugarcane	Corn, sorghum	Cotton	Coffee	Citrus / fruit, vineyards	Potato, cassave	Horticulture, ornamentals	Quinoa	Rice	Forest plantations	Various	Total
Argentina		25,000		13,950				65			62,000	150	101,165
Barbados								10					10
Belize													0
Bolivia	470,000	150,000			23,000	54,000	180,000		23,000				900,000
Brazil	32,557,100	7,188,180	12,013,340	1,845,640	344,460	68,990		27,000			1,600,000	500,000	56,144,710
Chile						25,572		20			32,000	6,972	64,564
Colombia		245,896			1,500	48,000		12,000		48,000	5,000		360,396
Costa Rica		4,800			4,000	6,850							15,650
Cuba		1,600,000					1,618					619,754	222,1372
Dominica													0
Dominican Repl.		114,742			62,500	1,400	1,070	1,293		174,389			355,394
Ecuador		40,000			10,000	18,297		3,072		720	5,524		77,613
El Salvador				1		1		1				1	4
French Guiana etc								1				1	2
Guatemala		156	20	17,600	100			100					17,976
Guyana											12,000		12,000
Haiti													0
Honduras		6,300	3,850		5,400	1,700	3,600	2,549		2,000			25,399
Jamaica						7,846							7,846
Mexico	10,000	276,608	82,094			115,899		64,355				21,516	570,472
Nicaragua		10,000	21		70			393		4,000			14,484
Panama		38,629						1					38,630
Paraguay	300,000												300,000
Peru		215,130	3,841	146,000	222	64,036	76	45,690	183	211		4,669	480,058
Puerto Rico													0
Remaining Caribs													0
Suriname								0.5					0.5
Trinidad & Tobago		15,000				2,000		350					17,350
Uruguay	500					320		290			145,020		146,130
Venezuela		35,867	855										36,722

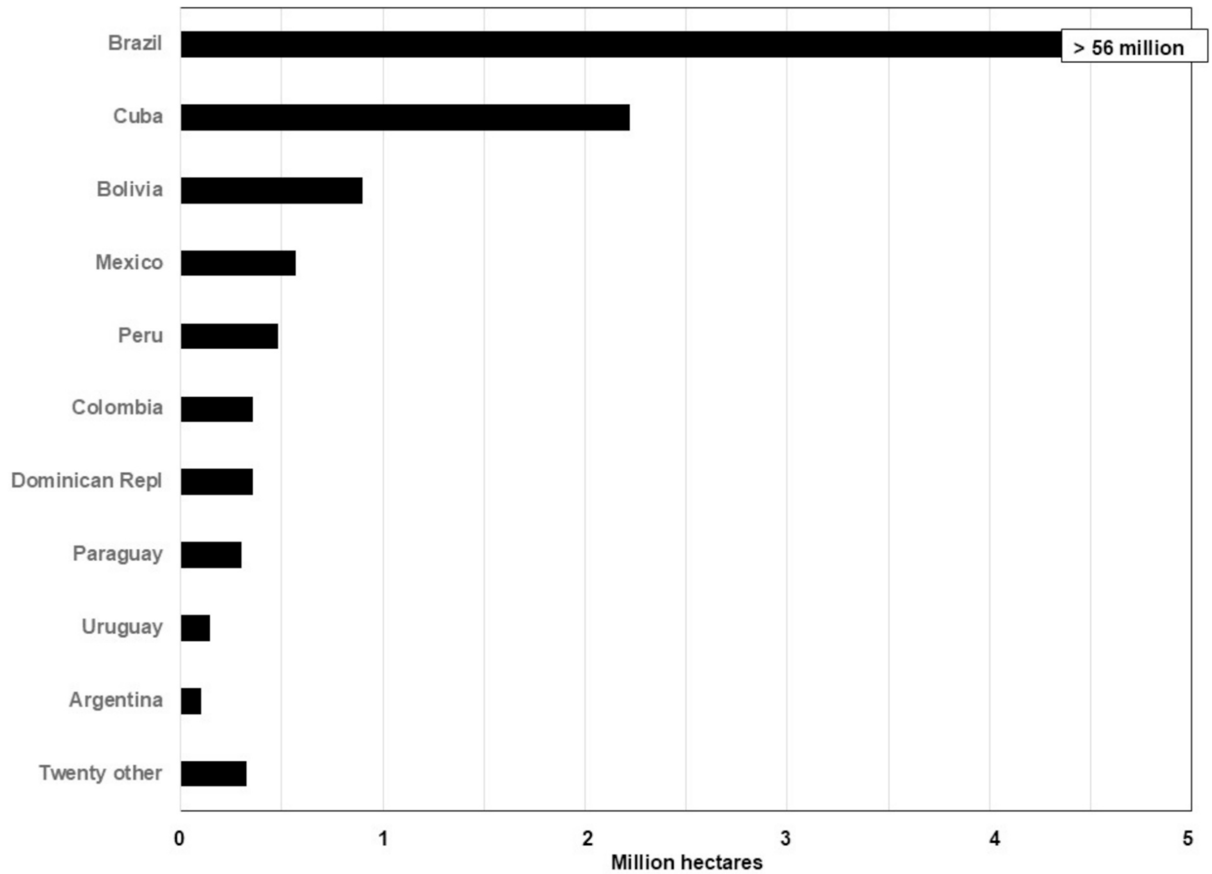

Fig. 1. Areas under augmentative biocontrol in millions of hectares for the 10 countries using most biocontrol in Latin America and the Caribbean in 2024 (data from Table 2 and 3, and references mentioned therein).

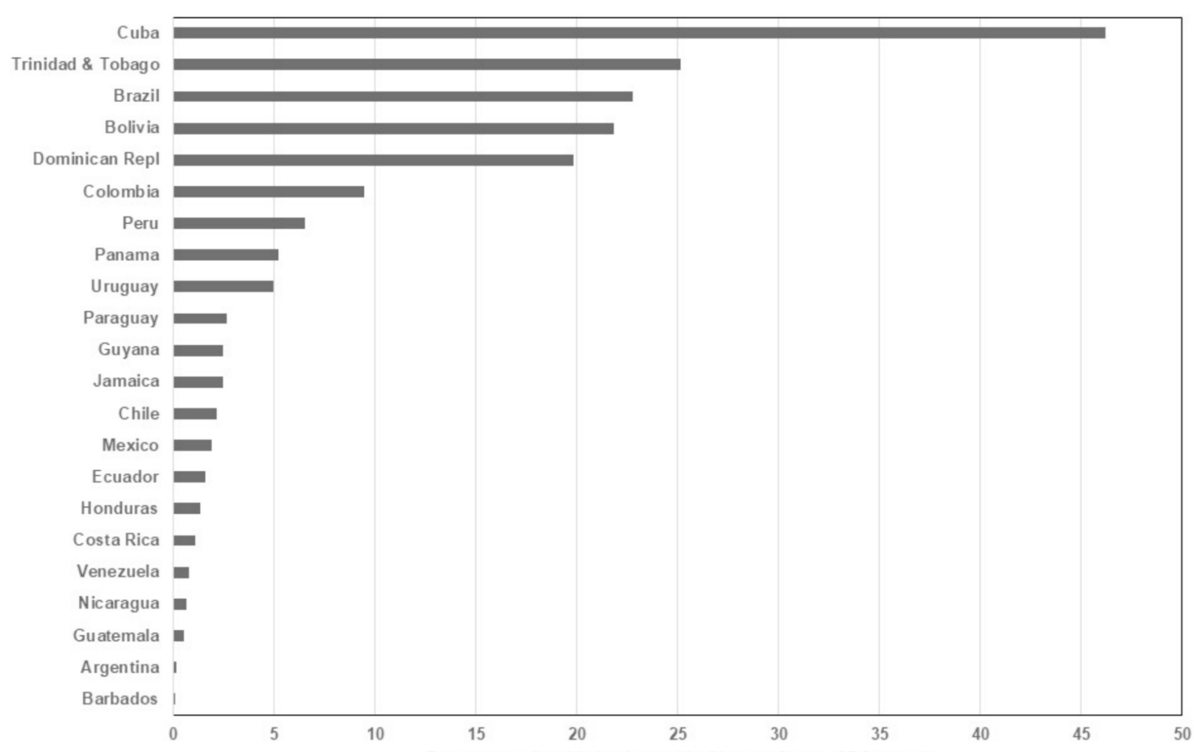

Fig. 2. Percentage of agricultural land treated with one of more augmentative biocontrol agents in countries of Latin America and the Caribbean in 2024 (data from Table 2 and 3, and references mentioned therein).

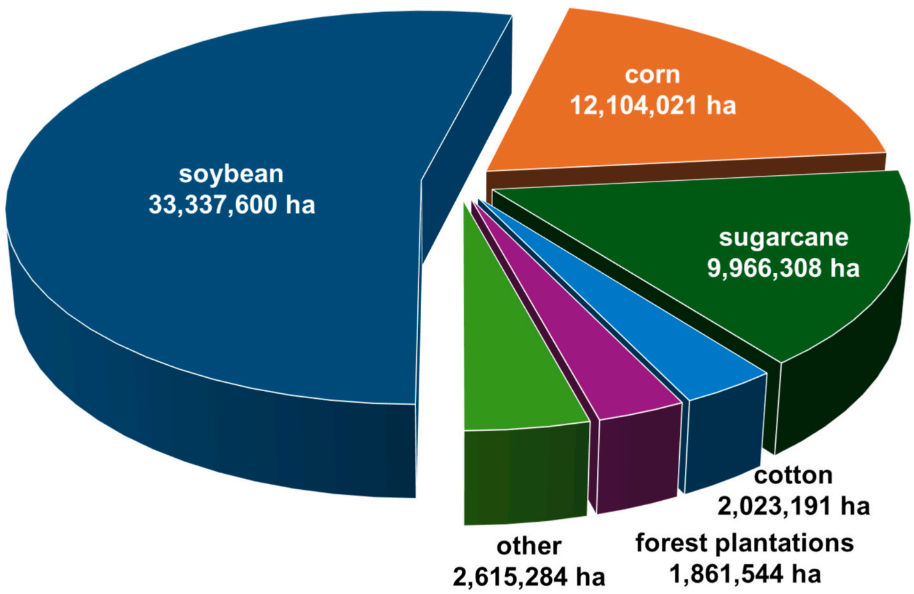

Fig. 3. Areas under augmentative biocontrol for the five largest crops using most biocontrol in Latin America and the Caribbean Caribbean in 2024 (data from Table 2 and 3, and references mentioned therein).

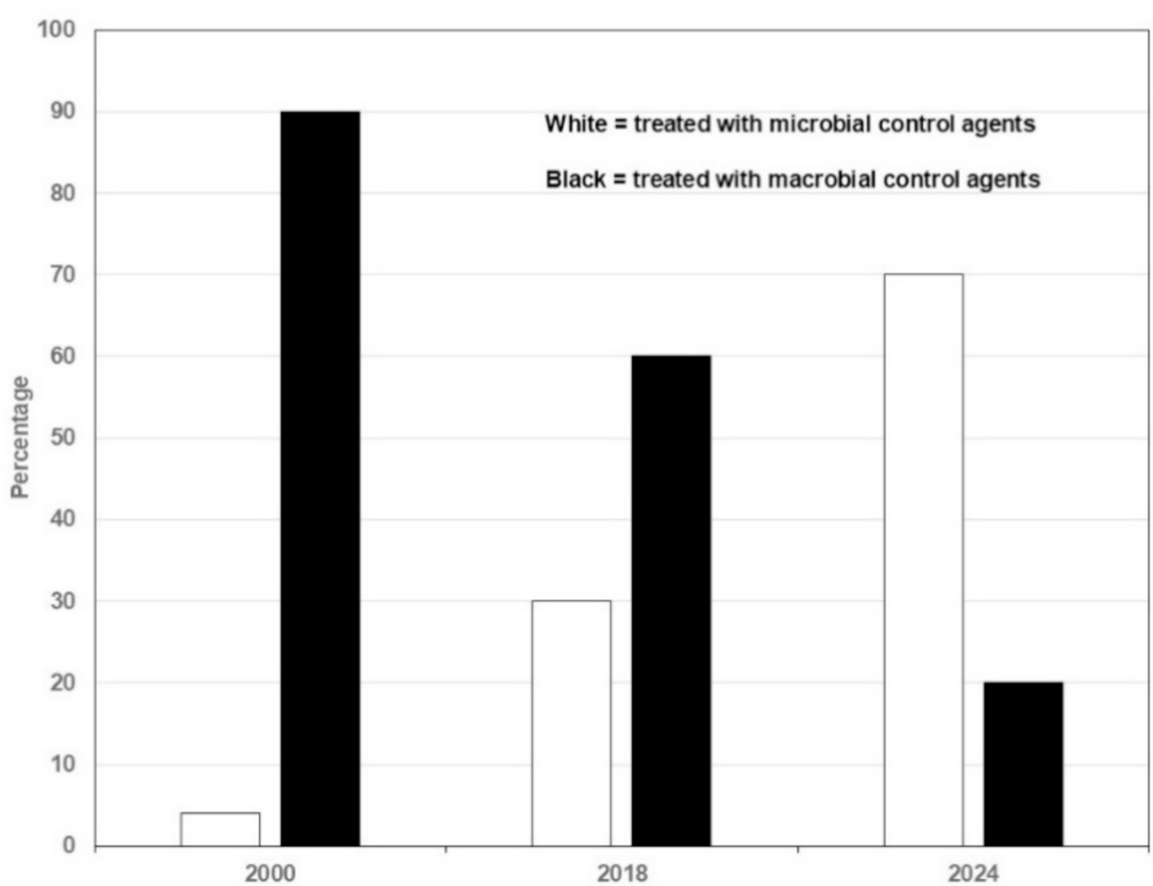

Fig. 4. Percentages of macro- and microbial control agents in augmentative biocontrol programmes used in 2000, 2018 and 2024 in Latin America and the Caribbean (data for 2000 from van Lenteren and Bueno (2003), data for 2018 from van Lenteren et al. (2020), data for 2024 from Table 2 and 3, and references mentioned therein). Total percentages for the three periods do not add up to 100% as for some crop areas the ABC agents were not clearly specified.

using a new biocontrol agent (e.g. BioFirst group (including Biotrop Brazil; https://biofirstgroup.com), Ballagro (https://ballagro.com.br) and Koppert (including Koppert do Brasil; https://koppert.com.br)).

The first criterion to choose for ABC concerns *availability*, which may sound obvious but it cannot always be met. Sometimes problems occur related to availability of biocontrol agents, as is currently happening for

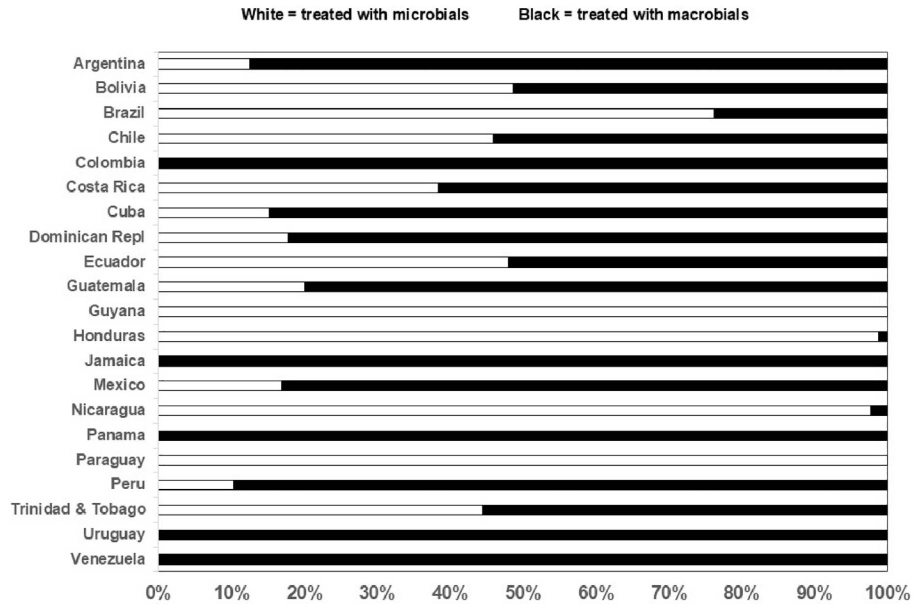

Fig. 5. Percentage of macro- and microbial control agents used in 2024 in Latin American and Caribbean countries (data from Table 2 and 3, and references mentioned therein).

Telenomus podisi Ashmead (Hymenoptera: Scelionidae) in Brazil (for details, see section 4.4).

A subsequent criterion is *affordability*. For farmers to accept a new control method, it is essential that the costs of an ABC programme for pests and diseases in a certain crop should be similar to the costs of a conventional synthetic chemical pesticide programme. In general, mass production of microbial agents is easier, and thus cheaper, than production of macrobial agents. Often, the production process of macrobial agents can be automated only partially and involves more steps than that of microbials. Thus, in general, ABC programmes based on the application of microbial control agents is cheaper than a programme using macrobial agents.

Applicability is another important criterion leading to the choice for a biocontrol agent. Taking the vast monocrop areas into account, it is essential that ABC agents can be applied to the crop quickly and easily, preferably by the often already available spray equipment. Nowadays, this is possible for most microbial agents (existing spray equipment and drones), but also for several – but not all – macrobial agents like parasitoids and predators.

Also *reliability* is a crucial issue when choosing for biocontrol. In the past, when quality control was lacking or poor, inferior agents were sold, resulting in a negative opinion about biocontrol. During the last 50 years, development and application of rigorous quality control programmes resulted in consistent ABC agent quality, a sufficiently long shelf life and this, together with proper transport conditions after production, caused reliable control of pests, diseases and weeds. In general, it is easier for microbials to satisfy this criterion than for macrobial agents, particularly for shelf life which is relatively short for macrobials. An additional problem for macrobials is the need of strictly maintained microclimate conditions when shipped from the production site to field locations.

Finally, *simplicity* in use of an ABC is relevant. The ABC method needs to be easy to understand for farmers, preferably based on simple biological working mechanisms in combination with preventive "calendar" treatments instead of treatments needing complicated sampling and decision-making programmes.

In case of dealing with thoroughly tested, registered biocontrol agents for which regular quality control protocols are applied, the above five criteria are usually met.

4.3. Other drivers stimulating use of ABC

Van Lenteren and Cock (2020) summarized what the authors of the country specific chapters in van Lenteren et al. (2020) mentioned about aspects that contributed to implementation of ABC.

An important development stimulating use of ABC was the design of *fine-tuned, fast and priority registration of BC agents.* The biocontrol industry is often frustrated by long procedures of 10 years or more to obtain governmental registration for new agents. Also, registration procedures are often not tailor made for biocontrol agents and, instead, remain largely similar to the procedure for conventional synthetic pesticides. Facilitating registration, as recently realized in Brazil, made it easier, quicker and cheaper to register agents (Anvisa, 2025; Bettiol et al., 2014, 2022; de Medeiros and Bettiol, 2023). In addition, prioritizing registration of biocontrol agents before chemical pesticides, and to register these agents per pest or disease and not per crop makes registration more attractive and easier (de Medeiros and Bettiol, 2023).

Governmental policies encouraging use of ABC are often mentioned as a factor stimulating use of ABC in the Latin American region and such policies have shown to result in increase in ABC in Bolivia, Cuba, Jamaica, Peru and recently in Brazil. In Brazil, the Ministry of Agriculture selected priority pests and diseases for registration of biocontrol agents (de Medeiros and Bettiol, 2023), resulting in at least one biocontrol agent for each important plant disease. Another Brazilian governmental decision made it possible to use on-farm produced biocontrol agents without the need of registration or quality control leading to increased areas under ABC (Fischer et al., 2023; de Medeiros and Bettiol, 2023).

Removal of highly toxic chemical pesticides from the market by several countries in the region have in the recent past prohibited the use of several of the most toxic pesticides, which opened new possibilities for biocontrol.

A very interesting initiative that might motivate use of ABC and other forms of biocontrol is a *pro-active approach in identifying future invasive species* in combination with the design of IPM methods to manage these species. Mexico (for more than 1000 exotic species, Arredondo-Bernal and Rodríguez-Vélez, 2020) and Jamaica (Sherwood and van Lenteren, 2020) use this approach to estimate what future problems to expect and design biocontrol and IPM programmes for potential invaders. Without this approach, most countries have to apply chemical pesticides to control a newly invading pest, not seldomly leading to termination of existing biocontrol programmes.

Export and local consumer demands for pesticide free food stimulated production of food under certification including the use of ABC. Examples of how export demands can accelerate use of ABC are programmes applied in Costa Rica (Blanco-Metzler and Morera-Montoya, 2020) and particularly in Peru (Mujica and Whu, 2020). An example of how consumer demands encourage use of ABC is given by Basso et al. (2020) for Uruguay.

A maybe unexpected reason to change to ABC is that *synthetic conventional chemical pesticides are no longer effective or not registered* for a certain pest. In 2013 in Brazil, the cotton bollworm *Helicoverpa armigera* (Hübner, 1809) (Lepidoptera: Noctuidae) was recorded, and at that time no chemical pesticide was registered for its control. Instead, a virus specific to *H. armigera* larva was used with success and changed the attitude of growers with regard to the use of biocontrol (Bueno et al., 2020). The development of resistance to chemical pesticides by arthropod pests and plant pathogens is a common and long existing problem worldwide, resulting in the need to develop alternative control methods like biocontrol.

Finally, a hopeful development is that a *change in attitude of farmers* towards acceptance of ABC methods is being perceived in the region. Older farmers grew up with the idea that pests, diseases and weeds could only be controlled by chemical pesticides, but young farmers are more willing to use alternative control methods such as ABC, as long as these methods are meeting the criteria of availability, affordability, applicability, reliability and simplicity.

Besides the above mentioned factors stimulating use of ABC in Latin America, there are inherent characteristic making biocontrol a preferred pest management method worldwide (van Lenteren et al., 2018). One of these is that farmers can always harvest, because use of biocontrol does not imply a "crop re-entry period" as is the case with most chemical pesticides. This allows them to optimize harvesting related to food price developments. Further, biocontrol agents seldomly cause health risks for farm workers and consumers, and biocontrol is more sustainable than chemical control as there is no or very slow development of resistance against these agents, though development of resistance against microbial control agents has been mentioned in the literature (Corey, 2017). Another advantage is that, contrary to the use of chemical control, application of macrobial biocontrol agents does not cause phytotoxic damage to plants and may, thus, result in increased yield. Microbial biocontrol agents are often applied together with adjuvants (surfactants, carriers, protectors and nutrients) to improve their performance, and there is a risk that these adjuvants may have negative effects on non-target organisms and the environment (Lin et al., 2023). Therefore, potential phytotoxic effects of adjuvants are studied before being used in field applications and when serious, the formulated microbial agents with these adjuvants will not be used by farmers (Wagner Bettiol, pers. comm. 2025). Lastly, a significant positive characteristic of using biological control is that biodiversity near the fields with crops is no longer negatively influenced due to pesticide drift and may show an increase.

4.4. Factors frustrating implementation of ABC

Despite all of the above mentioned positive qualities of ABC we cannot ignore that there are also still reasons why farmers may be hesitant to use biocontrol.

One of these is not meeting all of the first five criteria stimulating use of ABC, as this results in disappointments or even serious financial loss for the farmer due to crop damage. For example, ABC programmes may have to be terminated prematurely by insufficient availability of agents as in the case of control of the brown marmored stink bug *Euschistus heros* (Fabricius) (Hemiptera: Pentatomidae) in soybean in Brazil with the parasitoid *T. podisi*. Farmers desperately try to obtain this natural enemy because other satisfactory control methods are not available, but mass production of this parasitoid is rather complicated and companies currently cannot satisfy the demands of growers (J.R.P. Parra, pers. comm. 2024). However, according to H. Negri (pers. comm. 2025) mass production of *T. podisi* has recently been improved and 410,000 ha of soybean were treated with this parasitoid in 2024. An estimated 1 million hectares will be treated in 2025. Obviously, also high costs of biocontrol agents (affordability) do not motivate farmers to use ABC. Likewise, complicated and time consuming release of control agents (applicability) demotivate farmers to turn to ABC, as well as poor product quality and insufficient performance in the field (reliability). Finally, difficulty in understanding the biology of the biocontrol agent and complicated methods to determine the timing of the releases related to pest or disease presence make farmers decide not to choose for ABC.

A further cause hampering use of biocontrol is the overwhelming presence and power of the chemical pesticide industry. Van Lenteren and Cock (2020) in their summarizing chapter about biocontrol in Latin America stated: "… most persons now involved in crop protection matters – from the highest level in ministries of agriculture down to farmers and their workers – have been raised under the mantra "the only good insect is a dead insect, and chemical control is able to kill insects fast and cheap". The result is that many crop protection advisors and farmers are pesticide addicted after having heard this mantra for 70 years …". The power of the pesticide lobby in dominating the pest control market was mentioned in many of the country specific chapters in van Lenteren et al. (2020). However, during the past decades we start to perceive a change in attitude among young, well-educated farmers and their crop protection managers, particularly after experiencing good control of pest and diseases with ABC.

A well-known reason for poor functioning of ABC are negative non-target effects of chemical pesticides on biocontrol agents. When farmers apply both chemical pesticides and biocontrol agents, the failure of biocontrol agents to control a pest may erroneously attributed to the poor quality of the agents, while the explanation is that they have not been able to perform their task due to being eliminated by chemical pesticides. Reliable information about negative side-effects of chemical pesticides on biocontrol agents is available in English for a large number of active ingredients (see e.g. IOBC-WPRS, 2017), but this information is often difficult to understand for Spanish or Portuguese speaking farmers in Latin America.

The choice for biocontrol is also influenced by the unrealistically low costs of chemical pesticides. Application of the "true cost" principle for chemical pesticides would increase the market for biocontrol, because in that case an equal playing field is created. Pesticides are "subsidized" by governments, because the industry is usually not held responsible for human health problems including deaths, for reduction of biodiversity and preventing the functioning of ecosystem services of pest and disease control, pollination and cleaning of water. These costs are paid by the society. Application of the true cost principle would result in chemical pesticides being two to four times more expensive and a fairer competition with non-chemical control alternatives such as biocontrol (van Lenteren et al., 2018).

A worldwide problem hindering use of ABC is lack of taxonomic expertise. Rapid identification, and in case of finding a new biocontrol agent, a quick description of the new species are important for working with reliable biocontrol agents. Taxonomists able to identify natural enemies are few in number, and often scattered across museums and universities in the region. Taxonomic expertise is particularly important in the extremely biodiverse region of Latin America.

Worldwide, the complicated, time-consuming and expensive regulatory frameworks prevent biocontrol agents to quickly appear on the market. The currently very different procedures in the Latin American region result in the need to provide different documents for each country leading to high costs, so there is an urgent need for harmonization of regulatory frameworks. The positive influence of the development of fine-tuned, quick procedures for evaluation of new biocontrol agents by Brazil illustrates how this can help to boost application of ABC (see section 3.1).

4.5. Major differences with other regions where ABC is applied

In Latin American and the Caribbean most ABC programmes are applied in the open field. A common view is that ABC is particularly successful in greenhouses and less so in the open field, especially in Europe. The data presented in Table 3 show that this is a misconception, at least for the Latin American region: only 0.09 % of all ABC is applied in greenhouses, whereas 99,91 % is used in open field crops. Part of the explanation of the successes obtained in open field crops in Latin America is the predictability of weather conditions over longer periods, so that releases of biocontrol agents can be well planned and do not fail.

An additional important difference with other regions is that many ABC programmes in this region are using microbial control agents. In many Latin American countries, the use of microbials is more common than that of macrobials, and particularly control of soil-borne diseases and phytophagous nematodes is widespread. Of the total area under ABC in 2024 in Latin America, 72 % is treated with microbials and only 28 % with macrobials (Table 3). In Europe, the use of macrobials is still dominant although use of microbials is increasing fast.

Moreover, and in contrast with many ABC programmes in Europe and North America (Messelink et al., 2014; Pijnakker et al., 2020), the majority of ABC projects in this region are not aiming at obtaining resilient biocontrol systems. In the very large ABC programmes in Latin America for soybean, corn and sugarcane, frequent treatments of microbial and macrobial control agents are used, and a buildup of populations of macrobials to obtain a longer-term control effect is not intended. However, there are many interesting, smaller scale biocontrol programmes in Latin America and the Caribbean where the development of resilient systems is the main objective. Examples of such programmes are those in Bolivia and Cuba, where first the role of NBC and ConsBC is studied and when they do not sufficiently control the pest, CBC and/or ABC added (Franco et al., 2020; Márquez et al., 2020).

4.6. Concerns

The main message of this paper is that the use of ABC is strongly increasing in Latin America and the Caribbean, though we cannot ignore doubts that go together with these developments. Application of ABC in large monocropping systems to produce fodder for cattle and poultry is an important improvement because poisonous pesticides are replaced by environmentally safer solutions and with the benefit of being harmless for farm workers. Nevertheless, it is rather disappointing to observe that in several countries in this region hardly or no biocontrol is applied in food crops. Thus, the local human population does not profit from produce with low pesticide residue levels. Limited application of ABC in food crops might be explained by the relatively small areas on which these crops are grown, while most of the biocontrol industry is currently concentrating its activities on large monocrops providing a much larger financial benefit. It is therefore gratifying to see that there are also countries where considerable areas of food crops are under ABC, such as Bolivia, Chile, the Dominican Republic and Peru.

A next point of serious concern is that in countries where fodder production strongly increased, it was often at the cost of destroying large natural areas, e.g. by deforestation of tropical forest areas like in the Amazonas.

Furthermore, the soybean and corn ABC programmes now used to control plant diseases and invertebrate pests do reduce chemical pesticide use, but as these crops are based on the use of GM cultivars, the use of synthetic chemical herbicides is still very high (e.g. de Araujo et al., 2023), which negatively affects the environment.

Although application of ABC in Latin America has strongly increased during the past decades, we cannot ignore the fact that this region is also still a frontrunner in the use of synthetic chemical pesticides (de Araujo et al., 2023). This is, sadly, not only valid for registered chemical pesticides that are used in most other world regions, but also for a number of highly toxic “old” pesticides that are prohibited elsewhere (Das, 2024). Frequent use of pesticides, including the class of herbicides, is also known to have negative effects on development, reproduction and survival of invertebrate natural enemies in the environment (Zilnik et al., 2023).

4.7. Concluding remarks

The data concerning use of ABC during the past three decades (Table 1, 2 and 3) show an enormous growth of this form of biocontrol in Latin America and the Caribbean. This growth is for an important part the result of development and registration of a number of microbial control agents. The historical dominance of using macrobial agents shifted into application of microbial agents (Fig. 4), though not in all countries in the region (Fig. 5). The main reasons for this change are that microbial biocontrol agents are easier and cheaper to produce, have a much longer shelf life and can often be applied with spray equipment that farmers did use for chemical pesticides. An extraordinary characteristic of the use of ABC in this region is that, contrary to the situation in Europe and North America, it is almost exclusively applied in open field crops. Another notable difference with ABC programmes used elsewhere, is that the programmes in this region are often not specifically aimed at developing resilient systems. A final and important difference with use of ABC in other regions is that in Latin America application of ABC for a large part takes place in fodder crops and less so in food crops.

Author contributions to the paper

J.C. van Lenteren wrote the first draft, V.H.P. Bueno and W. Bettiol contributed to the draft and revised the paper. J.C. van Lenteren, V.H.P. Bueno and W. Bettiol collected the material, contributed to the analysis of data and assisted in making tables and figures. J.C. van Lenteren prepared the final version of the manuscript. All authors have read and approved the manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use generative AI and AI-assisted technologies.

CRediT authorship contribution statement

Joop C. van Lenteren: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Formal analysis, Data curation, Conceptualization. **Vanda H.P. Bueno:** Writing – review & editing, Visualization, Data curation, Conceptualization. **Wagner Bettiol:** Writing – review & editing, Visualization, Validation, Data curation.

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