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RESEARCH ARTICLE

The role of biological control in the sustainability of the Cuban agri-food system

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We analyze the role biological control plays in the Cuban agri-food system and discuss an experience at the country level that demonstrates that the pest problem can be handled through an ecological and sustainable approach. Biological control is one of the key components of a systemic approach that characterizes pest management. Its implementation has led to the removal of a group of highly dangerous pesticides from the Official List of Authorized Pesticides and reduced use of others. Greater emphasis has been placed on augmentative biological control, which is a tendency repeated throughout the world. In Cuba, rudimentary production occurs in 176 Centers for the Reproduction of Entomophages and Entomopathogens (CREE) located throughout the country; four industrial production plants are in operation, as are pilot plants and facilities in research centers. The biological control agents that are most reproduced are the parasitoids *Lixophaga diatraeae* (Townsend) (Diptera: Tachinidae) and *Trichogramma* Westwood (Hymenoptera: Trichogrammatidae), the entomopathogens *Bacillus thuringiensis* Berliner (Bacillales: Bacillaceae), and *Beauveria bassiana* sensu lato (Bals.-Criv.) Vuill. (Hypocreales: Cordycipitaceae); the antagonist *Trichoderna* Persoon (Ascomycota: Hypocreales: Hypocreaceae); and the nematodes of the *Heterorhabditis* Poinar (Nematoda: Rhabditida: Heterorhabditidae) genus. The use of predatory mites in inoculative strategies is limited due to their restricted availability, in spite of the fact that different alternatives have been evaluated for their massive reproduction with encouraging results. The achievements and progress obtained in classical and augmentative biological control and the changes in the understanding and thinking in Cuban agricultural have laid strong foundations for biological control through conservation of natural enemies. This latter strategy is greatly valued in sustainable agriculture. *Please refer to Supplementary Materials*, DOI: https://doi.org/10.1525/elementa.326.s1, *for a full text Spanish version of this article.*

Keywords: Biological control; Agroecology; Cuba; Control biológico; Agroecologia

Se analiza el modo en que el control biológico está insertado en el sistema agroalimentario cubano y se presenta una experiencia a escala de país que demuestra que los problemas de plagas se pueden enfrentar desde una perspectiva ecológica y sostenible. El control biológico es uno de los componentes claves del enfoque sistémico que caracteriza el manejo de plagas, su implementación ha permitido la retirada de un grupo de Plaguicidas Altamente Peligrosos de la Lista Oficial de Plaguicidas Autorizados, y la disminución en el uso de otros. El énfasis mayor ha sido puesto en el control biológico aumentativo, esa es la tendencia seguida en todo el mundo. La producción artesanal se realiza en 176 Centros de Reproducción de Entomófagos y Entomopatógenos, distribuidos por todo el territorio nacional; funcionan cuatro plantas de producción industrial y plantas e instalaciones pilotos en los centros de investigación. Los agentes de control biológico que en mayor cantidad se reproducen son: los parasitoides *Lixophaga diatraeae* (Townsend) (Diptera: Tachinidae) y *Trichogramma* Westwood (Hymenoptera: Trichogrammatidae), los entomopatógenos *Bacillus thuringiensis* Berliner (Bacillales: Bacillaceae) y *Beauveria bassiana* sensu lato (Bals.-Criv.) Vuill. (Hypocreales: Cordycipitaceae), el antagonista *Trichoderna* Persoon (Ascomycota: Hypocreales: Hypocreaceae), y los nematodos del género *Heterorhabditis* Poinar (Nematoda: Rhabditida: Heterorhabditidae). El uso de ácaros depredadores en estrategias inoculativas está limitado por su escasa disponibilidad, a pesar de que se han evaluado diferentes alternativas para su reproducción masiva con resultados alentadores. Los logros y avances alcanzados en el control biológico clásico y aumentativo y los cambios producidos en la visión y en el pensamiento agrícola cubano han sentado sólidas bases para el control biológico por conservación de enemigos naturales. Esta última es la estrategia que tiene un verdadero valor para la agricultura sostenible. *La versión en español de este artículo se puede encontrar en Materiales Suplementarias*, DOI: https://doi.org/10.1525/elementa.326.s1.

Palabras clave: Control biológico; Agroecologia; Cuba; Control biológico; Agroecologia

Introduction

In the past 20 years, global public awareness has grown regarding the dangers of using chemical-synthesis pesticides. Increased awareness is due to numerous actions undertaken by many organizations and institutions throughout the world. Outstanding activities include the advances in scientific knowledge of the negative impacts of pesticide use on human, animal, soil, and ecosystem health (Pretty, 2005; Viewege et al., 2014; IARC, 2015a, 2015b; TFSP, 2015); the existence of legally binding international conventions and treaties (i.e., Rotterdam, Stockholm, and Montreal) regarding the use of these substances (Weinberg, 2008); the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) calls to governments since 2006 for the gradual elimination of Highly Dangerous Pesticides (HDP) (FAO, 2006); approval of the "Strategic Approach to International Chemical Management" (SAICM) (UNEP, 2006); and a list of highly dangerous pesticides published since 2009 by the Pesticide Action Network (PAN International, 2016). Among the most notable recent actions is the fact that at the 34th period of sessions of the United Nations Human Rights Council, held from February 27 to March 24, 2017, the Special Rapporteur on the Right to Food, Hilal Elver, recommended going beyond voluntary measures so that the international community could prepare a broad and binding treaty that included "drafting policies to reduce the use of pesticides throughout the world and a framework for progressively prohibiting and eliminating highly dangerous pesticides" (UN, 2017).

In this brief description of public policies and political instruments, what role does biological control (BC) play? First, BC is among the main alternatives to the use of pesticides. Successful experiences in various countries demonstrate its positive and undeniable pest-management role in sustainable agriculture (Bettiol et al., 2014; Parra, 2014; Cock et al., 2016; van Lenteren et al., 2017).

Currently, different schools of BC coexist, but for the majority the foundational principle is based on rudiments of insect ecology and on reducing broad-spectrum-action pesticides (Warner et al., 2011). The following is among the most widely accepted BC definition: "The use of living organisms to suppress the population density or impact of a specific pest organism, making it less abundant or less damaging than it would otherwise be" (Eilenberg et al., 2001, p. 390). A considerable number of organisms can be used as biological control agents (BCA). More than 440 BCA species are available on the market (van Lenteren et al., 2017). Today Latin America and the Caribbean are among the regions where the BCA market is experiencing significant growth (van Lenteren, 2012; van Lenteren et al., 2017). In 2012, this region was the fourth among five regions in BCA sales (Veronelli, 2012; van Lenteren et al., 2017).

In the fullest sense of the concept, BC in Cuba has a lengthy and rich history that has involved learning about natural biological control (NBC) and applying three BC strategies: classical biological control (CBC), augmentative biological control (ABC) (inundative and inoculative), and conservation biological control (CBC). Studies on NBC allow us to identify, partially, the diversity of endemic and native species of natural enemies and understand the principles and relationships that sustain the ecosystem services of natural pest control (van Lenteren, 2006; Gillespie and Wratten, 2012). BC is one of the key components of the systemic approach that characterizes both the comprehensive and ecological management of pests. Its implementation has led to the removal of a number of highly dangerous pesticides from the Official List of Authorized Pesticides of the Republic of Cuba (MINAG, 2016) and to decreased use of other pesticides (Pérez et al., 2010). A historical analysis of advances in this field reveals that there has been steady progress, in spite of the country's economic difficulties that undoubtedly hinder scientific research and the dissemination, application, and extension of results to society.

We understand that the success of BC depends heavily on governmental investment in research and development and on the institutions whose goals include reducing the incidence of pesticides (Bale et al., 2008). During the height of the economic crisis of the 1990s in Cuba, a percentage of the country's scarce funds were channeled to continuing research and development of BC, and greater efforts were made to reduce the incidence of pesticides. What occurred was not simply a substitution of inputs, as is often done in other places; the idea was never, nor is it now, "eliminate a chemical to substitute a biological agent."

The triad consisting of the concepts of sustainability, sustainable agriculture, and agroecology arrived in Cuba along with the economic crisis triggered by the fall of the socialist countries. This was the starting point of past and present transformations in Cuban agriculture on a national scale. By 1990, the two National Programs of Biological Control that began in the 1980s (see **Table 1**) had sufficiently advanced to address the challenges of the period related to plant health.

The close scientific collaboration with the countries of the ex-socialist block, especially in alliance with the USSR, notably contributed to advances in the countryside with augmentative biological control, which to a certain extent helped Cuba to acquire what today we call technological sovereignty, i.e., the use of technologies that at that moment were possible and necessary: rudimentary, local, and low-input technologies. Without consciously planning to do so (because in Cuba it was difficult to imagine the downfall of the socialist bloc), we were building resilience to a certain degree. The word "resilience" later became a part of our vocabulary, because the word "resistance," which has a different meaning, was always present. This article explains how BC helped, and continues helping, the sustainability of the Cuban agri-food system, and outlines a country-level experience that demonstrates that pest problems can be addressed with an ecological and sustainable focus.

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Table 1: Chronology of cases and notable events related to biological control in Cuba (1904–2016). DOI: https://doi.org/10.1525/elementa.326.t1

Year	Case or event	Natural enemy	Pests	References
1904	Creation of the Central Agronomic Station in Santiago de las Vegas (today known as the Alexander von Humboldt Institute of Fundamental Research in Tropical Agriculture).			Martínez, 2004
1906	Annual Report 1904–1905 Central Agronomic Station, part of the publication *Algunas Coccinellidae de Cuba* by George W. Dimmock.	Coccinellids	Mostly aphids, coccids, pseudococcids, white flies, and mites	Dimmock, 1906
1914	For the first time Wolcott observed a parasitoid on borer larva of a sugarcane stalk (*Saccharum* spp. L.), with a wide dispersion in the sugarcane fields of the provinces of Matanzas, Havana, Las Villas, and Oriente.	*Lixophaga diatraeae* (Townsend) (Diptera: Tachinidae)	*Diatraea saccharalis* Fabricius, sensu Guenée (Lepidoptera: Crambidae)	Fernández, 2002
1917	First introduction of a predator insect.	*Cryptolaemus montrouzieri* Mulsant (Coleoptera: Coccinellidae)	*Pseudococcus* spp. (Hemiptera: Pseudococcidae)	Milán et al., 2005 Kairo et al., 2013
1928	Second introduction of a predator.	*Rodolia cardinalis* (Mulsant) (Coleoptera: Coccinellidae)	*Icerya purchasi* Maskell (Hemiptera: Monophlebidae)	DeBach and Rosen, 1991
1930–1931	Three parasitoids imported from Singapore for release in citrus fields (*Citrus* spp. L.).	*Eretmocerus serius* Silvestri, (Hymenoptera: Aphelinidae)	*Aleurocanthus woglumi* Ashby (Hemiptera: Aleyrodidae)	DeBach and Rosen, 1991
		Encarsia divergens Silvestri (Hymenoptera: Aphelinidae)	*A. woglumi*	DeBach and Rosen, 1991
		Encarsia smithi Sivestri (Hymenoptera: Aphelinidae)	*A. woglumi*	DeBach and Rosen, 1991
1930	Curtis P. Clausen imported two predators to be used in citrus plantations.	*Catana clauseni* Chapin, (Coleoptera: Coccinellidae)	*A. woglumi*	DeBach and Rosen, 1991
		Scymnus smithianus Silvestri (Coleoptera: Coccinellidae)	*A. woglumi*	DeBach and Rosen, 1991
1930s	L. C. Scaramuzza begins studies of biology, reproduction, and release of the Cuban fly. This is arguably the starting point for the development of applied biological control in Cuba.	*L. diatraeae*	*D. saccharalis*	Fernández, 2002
1934–1939	Introduction of two parasitoids.	*Paratheresia claripalpis* van der Wulp (Diptera: Tachinidae) *Metagonistylum minense* Townsend (Diptera: Tachinidae)	*D. saccharalis*	Fernández, 2002
1945	Inauguration of the first biological control laboratory for reproduction and sale of *L. diatraeae*, in the sugar workers' town of the *Mercedes* central (today known as *Seis de Agosto*).	*L. diatraeae*	*D. saccharalis*	Fernández, 2002

(Contd.)

Year	Case or event	Natural enemy	Pests	References
1960s	Second introduction of de *C. montrouzieri*.	*C. montrouzieri*	Pseudococcids	Kairo et al., 2013
	The first microbial bio-pesticides arrive in the country to control the larva of lepidopterans in tobacco (*Nicotiana tabacum* L.) and grasses.	*Bacillus thuringiensis* Berliner (Bacillales: Bacillaceae)	*Heliothis virescens* Fabricius (Lepidoptera: Noctuidae) *Mocis latipes* Guenée (Lepidoptera: Erebidae)	Fernández-Larrea, 2013
	Study by Salvador de la Torre y Callejas of native species of a parasitoid of eggs. His research contributed basic knowledge for the development of a mass-production technology.	*Trichogramma* Westwood (Hymenoptera: Trichogrammatidae)	Eggs of lepidopterans	Fuentes, 1994
	Development of technologies and construction of the Centers for the Reproduction of Entomophages and Entomopathogens (CREE) for the rudimentary production of microbial and macrobial biological control agents.	*B. thuringiensis* *Trichogramma* spp.	*D. saccharalis* *M. latipes* *H. virescens* *Erinnyis ello* L (Lepidoptera: Sphingidae) *Plutella xylostella* L. (Lepidoptera: Plutellidae)	Fernández-Larrea, 2007 Massó, 2007
1970s	Studies begin with entomopathogenic nematodes at the Institute of Research on Citrus and other Fruits (today renamed Institute of Tropical Fruit Growing).	*Heterorhabditis heliothidis* (Khan, Brooks & Hirschmann) (Nematoda: Rhabditida: Heterorhabditidae)	*Pachnaeus litus* (Germar, 1824) (Coleoptera: Curculionidae)	Rodríguez et al., 2012
	The rudimentary production of two entomopathogenic fungi begins.	*Beauveria bassiana* sensu lato (Bals.-Criv.) Vuill. (Hypocreales: Cordycipitaceae) *Metarhizium anisopliae* sensu lato (Metsch.) Sorokin (Hypocreales: Clavicipitaceae)	*Cosmopolites sordidus* (Germar) Marshall, G.A.K. (Coleoptera: Curculionidae) *Cylas formicarius* (Fabricius) (Coleoptera: Brentidae) *Tagosodes oryzicolus* (Muir) (Hemiptera: Delphacidae) *P. litus*	Fernández-Larrea, 2007
	Investigations begin with predator mites of the Phytoseiidae family.	More than 60 species were reported on, belonging to 20 genera.	Phytophagous mites	Rodríguez et al., 2013
1980	The Ministry of Sugar established the National Program of Biological Control.			Fuentes et al., 1998
1982	Declaration of a Comprehensive Management of Pests as a policy of the Cuban state.			Pérez, 2007
1988	The Ministry of Agriculture approves the National Program for Production of Biological Controls.			Fuentes et al., 1998

(Contd.)

Year	Case or event	Natural enemy	Pests	References
1990s	Further research with parasitoids of the Spodoptera complex and other lepidoptera. Biological studies were undertaken and methodologies prepared for the massive reproduction of six parasitoids.	*Telenomus* Haliday (Hymenoptera: Platygastridae)	*Spodoptera frugiperda* J. E. (Smith) (Lepidoptera: Noctuidae)	Fuentes et al., 1998
		Euplectrus platyhypenae Howard (Hymenoptera: Eulophidae)	*S. frugiperda* *Spodoptera eridania* (Stoll) (Lepidoptera: Noctuidae) *Leucania* Ochsenheimer (Lepidoptera: Noctuidae)	
		Archytas marmoratus Townsend (Diptera: Tachinidae)	*S. frugiperda* *Leucania unipuncta* Harworth (Lepidopera: Noctuidae)	
		Chelonus insularis Cresson (Hymenoptera: Braconidae	Complejo *Spodoptera* Guenée (Lepidoptera: Noctuidae)	
		Rogas Nees von Esenbeck (Hymenoptera: Braconidae	Complejo *Spodoptera*	
		Eucelatoria Townsend (Diptera: Tachinidae)	*S. frugiperda* *L. unipuncta*	
	The National Center of Agricultural Health undertakes its first prospective studies of entomopathogenic nematodes.	*Heterorhabditis* Poinar (Nematoda: Rhabditida: Heterorhabditidae) *Steinernema* Travassos, (Nematoda: Rhabditida: Steinernematidae)	Lepidoptera, beetles, and pseudococcids on sugarcane, citrus, coffee trees (*Coffea arabica* L. and *Coffea canephora* L.), pineapple (*Ananas comosus* (L.) Merr.), and vegetable crops	Rodríguez et al., 2012
	Studies continue with predatory mites of the Phytoseiidae family.	*Phytoseiulus macropilis* Athias-Henriot (Acari: Phytoseiidae)	*Tetranychus tumidus* Banks (Acari: Tetranychidae) and *Panonychus citri* (McGregor) (Acari: Tetranychidae), in banana (*Musa* L.) and citrus nurseries.	Rodríguez et al., 2013
1994–1996	Mass production of two parasitoids begins in the provinces of Havana, Villa Clara, and Sancti Spíritus, which are included in a program of comprehensive pest management.	*Telenomus* spp. *E. platyhypenae*	Complejo *Spodoptera* *Leucania* spp.	Fuentes et al., 1998
1995	50 centers in operation for the reproduction of *L. diatraeae*, which release up to 78 million flies over 1.6 million hectares.			Fuentes et al., 1998
1995–1998	Release of a new parasitoid from Brazil, Venezuela, and Peru for use on sugarcane plantations.	*Cotesia flavipes* Cameron (Hymenoptera: Braconidae)	*D. saccharalis*	Rodríguez et al., 2001
2000	Third introduction of *C. montrouzieri.*	*C. montrouzieri*	Pseudoccócidos	Milán et al., 2005 Kairo et al., 2013

(Contd.)

Year	Case or event	Natural enemy	Pests	References
2003	Introduction of the Ivory Coast wasp, parasitoid of the borer beetle of the fruit of the coffee tree from Mexico.	*Cephalonomia stephanoderis* Betrem (Hymenoptera: Bethylidae)	*Hypothenemus hampei* Ferrari (Coleoptera: Scolytidae)	Peña et al., 2006 Murguido et al., 2008
2004	A Commission of Agricultural Biotechnology Priority Products is formed within the Ministry of Agriculture that analyzed results obtained in the branch research programs of the National Scientific and Technical Program "Agricultural Biotechnology."			Fernández-Larrea, 2013
2006	Introduction of the Togo wasp, parasitoid of the borer pest in the coffee tree from Mexico.	*Phymastichus coffea* LaSalle (Hymenoptera: Eulophidae)	*H. hampei*	Rodríguez et al., 2007
2010	Production of entomopathogenic nematodes in 33 CREEs. 700 million infective juveniles are produced monthly.	*H. bacteriophora* cepa HC1	Lepidoptera pests in sugarcane and other crops.	Rodríguez et al., 2012
	The Commission for Agricultural Biotechnology Priority Products presents a project for large-scale production of the most requested microbial biological control agents, biopesticides of botanical origin, biostimulants, and biofertilizers.			Fernández-Larrea, 2013
2011	Approval is granted to the project presented by the Commission for Agricultural Biotechnology Priority Products and is currently implemented by the LABIOFAM Entrepreneurial Group.			Fernández-Larrea, 2013
2013	Introduction of an endoparasitoid of the pink bedbug of the hibiscus (*Hibiscus*), from the Island of Margarita, Venezuela.	*Anagyrus kamali* Moursi (Hymenoptera: Encyrtidae)	*Maconellicoccus hirsutus* (Green) (Hemiptera: Pseudococcidae)	Jiménez et al., 2015
2013	Four plants for the production of biopesticides and 176 Centers for the Reproduction of Entomophags and Entomopathogens are in operation, as well as plants and pilot facilities in research centers.			Fernández-Larrea, 2013
2015	Review of Cuban agro-environmental policies.			Febles, 2016
2016	Removal of the following highly dangerous pesticides from the Official List of Authorized Pesticides: methamidophos, parathion-methyl, and methiocarb.			MINAG, 2016
2016	Activity F, "Undertake actions that contribute to the agroecological management of pests" is included in the document, "Cuba: National Goals for Biological Diversity 2016–2010.			CITMA, 2016

Important moments in the history of biological control in Cuba

The history of BC in Cuba dates back more than 100 years (Massó, 2007). The beginning is in some way similar to that of other countries: observation of natural control activity such as parasitism, parasitoidism, predation, and diseases, and the introduction of natural enemies.

During the first half of the 20th century, several natural enemies were imported but, over time, there were few introductions (**Table 1**). Greater attention has been focused on ABC, but unlike other parts of the world, in Cuba, as in Argentina and Brazil, most of the natural enemies used in ABC are not introduced species (van Lenteren, 2012). In Pérez (2007), more detailed information is available regarding the historical evolution of BC in Cuba.

The cases and events covered in **Table 1** substantiate the advances and validate the current tendency of conservation biological control as an ecosystem service for the natural regulation of pests in Cuba. Accumulated experience in classical biological control and augmentative biological control laid the foundation for progress during the second decade of the 21st century as the country advanced towards conservation biological control.

Initially inventories were drawn up and explorations were undertaken in order to explore the unknown biodiversity of the main groups of endemic natural enemies with a potential to become biological control agents (Milán et al., 2008; Ceballos et al., 2011; Rodríguez et al., 2012; Gómez et al., 2012). Today that objective remains (Hernández-Ochandía, 2014; Hastie-Navarro et al., 2014) and two others have been added: establish a baseline in order to identify tendencies in fluctuations of biological diversity and gather information that substantiates and facilitates the implementation of policies and strategies for their conservation management.

Classical biological control

CBC is the intentional introduction of an exotic biological control agent for its permanent establishment and long-term control purposes (Eilenberg et al., 2001). The country with the highest number of releases of natural enemies as part of a CBC strategy is the United States: 1,956 releases between 1870 and 2010 (Cock et al., 2016). In Latin America and the Caribbean, the number of releases of natural enemies varies by country. Of the 33 countries in the region, in eight there have been more than 40 releases during the same period of time: Chile 95, Barbados 87, Trinidad and Tobago 78, Mexico 74, Peru 51, Bahamas 49, Brazil 48, and Saint Kitts and Nevis 47 (Cock et al., 2016). In Cuba, there have been less than 20 imports of entomophagous insects between 1910 and 2010.

In 1917, Mario Calvino, director of the Experimental Agronomic Station at Santiago de las Vegas, carried out the first introduction of a natural enemy. The predator *C. montrouzieri* was imported from California to be used on sugarcane, banana, and pineapple plantations, as well as on other crop varieties to control *Pseudococcus* spp. (Milán et al., 2005; Kairo et al., 2013). *C. montrouzieri* did not establish itself and over time it was necessary to carry out further introductions.

The second import of *C. montrouzieri* occurred in the 1960s from the USSR (Kairo et al., 2013), and the third in 2000 from Trinidad and Tobago, in light of the forecasted entry into Cuba of *Maconellicoccus hirsutus* (Green) (Hemiptera: Pseudococcidae). A methodology for its mass reproduction was drawn up; the breeds were carried out in 13 provincial plant-health laboratories and releases began thereafter (Milán et al., 2005). This was one of the few natural enemies introduced in Cuba using ABC.

In 1928, in response to a proposal by S.C. Bruner and O. Arango, *R. cardinalis* was introduced from Florida, United States, for the control of *I. purchasi*, the cottony cushion scale of citrus (DeBach and Rosen, 1991). *R. cardinalis* became established and resulted in effective control that continues today.

Between 1930 and 1931, there were five imports of two predators, *C. clauseni* and *S. smithianus*, and three parasitoids, *E. serius*, *E. divergens*, and *E. smithi*, for the control of *A. woglumi* (citrus blackfly) (DeBach and Rosen, 1991). *E. serius* was permanently established and *A. woglumi* ceased to be a pest, such that it is now called an insect relic. The report prepared by Cock et al. (2009) for the FAO's Genetic Resource Commission lists this as one of the most notable success stories in the introduction of natural enemies. Yet *C. clauseni* did not become established, even though it persists in very small populations in crops other than citrus (DeBach and Rosen, 1991). Some years ago it was found in the Sierra del Rosario, Pinar del Río, during a study on beetles carried out between 2001 and 2005 (Fernández et al., 2014). *S. smithianus* was unable to established itself either.

The end of the 1930s brought a phase of CBC to a close. Between 1934 and 1939 L. C. Scaramuzza introduced two parasitoids from Brazil to be mass reproduced and released in sugarcane fields: *P. claripalpis* and *M. minense* (Amazon fly) (Fernández, 2002). Imports were later to continue but at a much slower pace. The last introduction, of *A. kamali*, is more recent, imported from the Island of Margarita for the control of *M. hirsutus* (Jiménez et al., 2015).

From this overview, we can see that the CBC strategy is not what has predominated in BC in Cuba. The introduction of natural enemies has its risks, but there was no awareness of potential problems until late in the 20th century. It is possible for certain imported species to become invasive species, which has occurred in various regions of the world with the general predator *Harmonia axyridis* (Pallas) (Coleoptera: Coccinellidae) (Evans y Snyder, 2011; Koren et al., 2012; Bahlai et al., 2014).

Augmentative biological control, what is visible

ABC is the use of live organisms for pest control when control is being done exclusively by the organism that was released (Eilenberg et al., 2001). ABC involves mass production and release of large quantities of natural enemies and constitutes a solution for reducing or eliminating the use of pesticides. ABC is the strategy that has been prioritized in Latin America and the Caribbean and in Cuba.

Research in this area during the 1980s and 1990s was characterized by a search for native natural enemies (insects, bacteria, fungi, nematodes, and mites), bioecology studies, possible target organisms, methods of rudimentary and semi-industrial mass reproduction (for bacteria and fungi), efficiency tests, ecotoxicology, and methods of release and/or application (Fernández-Larrea, 2007; Massó, 2007; Rodríguez et al., 2012; Hidalgo, 2013; Rodríguez et al., 2013).

Entomophagous insects

Entomophagous insects used as ABC can be divided into two groups: parasitoids and predators. Cuba has emphasized research with parasitoids and especially those of two genera, the tachinid fly *Lixophaga* and the tiny wasp *Trichogramma* (**Table 2**).

After reviewing the history of BC in Cuba and the world, it is not difficult to understand why this tendency persists. *L. diatraeae* is a parasitoid of *D. saccharalis*, the insect that produces the greatest losses in sugarcane (this has been one of the Cuban economy's most important crops since the 18th century), and *Trichogramma* is the most used parasitoid in ABC programs in the world.

Predatory insects have received less attention than parasitoids. The latter are produced in limited numbers to be used in inoculative releases, depending on the needs of each region. Until around 2005, the predators that were most produced by the CREE were the chrysopidae; this tendency changes following the reintroduction of the coccinellid *C. montrouzieri* in 2000. In 2007, *C. montrouzieri* was being reproduced in 16 CREEs and *C. cubensis* in two (Massó, 2007). Entomophagous insects (parasitoids and predators) are not formally registered in Cuba.

Entomophagous mites

Research on predatory mites began later than on entomophagous insects. The taxonomic identification of mites from the Phytoseiidae family began in the 1970s. The Phytoseiidae are the most common natural enemies of the phytophagous mites; 20 genera and more than 60 species have been documented (Rodríguez et al., 2013). Among the most studied species are *P. macropilis* and *Amblyseius largoensis* (Muma) (Acari: Mesostigmata: Phytoseiidae) (Rodríguez et al., 2013; Hastie-Navarro et al., 2014). Unlike other BCA groups, the use of these predators in inoculative strategies has been limited by their scarcity, in spite of the fact that different alternatives have been studied for mass reproduction with encouraging results (Rodríguez et al., 2013). They are currently being reproduced solely in the CREE of Villa Clara province. Studies on the effectiveness of new species and mass reproduction methods continue (Pérez et al., 2014; Rodríguez et al., 2015). Predatory mites are not formally registered in Cuba.

Microbial biological control agents

Microbial biological control agents (MBCA) appeared on the scene when there was a certain awareness and understanding of the need and importance of using insects as BCA. The MBCA produced in Cuba belong to the following groups: bacteria and entomopathogenic fungi (Fernández-Larrea, 2013), antagonistic fungi (Martínez et al., 2013), and bacteria and nematophagous fungi (Hidalgo, 2013; Marín et al., 2013). Research has been done on antagonistic bacteria and with entomopathogenic virus, but the BCA that belong to the groups are not in a mass-production phase; no research is carried out on protozoans.

The MBCA that are most produced are the bacteria *B. thuringiensis*, the entomopathogenic fungi *B. bassiana*, and the antagonistic fungi *Trichoderma* spp. For many years *B. thuringiensis* was the only bacteria produced in the country to control harmful organisms on agricultural crops. More

Table 2: Principal parasitoid and predator insects reproduced in the Centers for Reproduction of Entomophages and Entomopathogens, hosts, and prey that they consume, Cuba 1998–2007. DOI: https://doi.org/10.1525/elementa.326.t2

Parasitoids/predators	Order: Family	Hosts/prey
Trichogramma spp. Westwood	Hymenoptera: Trichogrammatidae	Parasitoid of lepidoptera eggs
Lixophaga diatraea (Townsend)	Diptera: Tachinidae	Parasitoid of *Diatraeae saccharalis* and other lepidoptera larva
Eucelatoria sp. (Townsend)	Diptera: Tachinidae	Parasitoid of lepidoptera larva
Tetrastichus howardi (Olliff)	Hymenoptera: Eulophidae	Parasitoid of insect pupae
Euplectrus sp. Howard	Hymenoptera: Eulophidae	Parasitoid of immature insects
Telenomus sp. Haliday	Hymenoptera: Platygastridae	Parasitoid of lepidoptera eggs
Cephalonomia stephanoderis Betrem	Hymenoptera: Bethylidae	Parasitoid of adult borers of the coffee tree
Cryptolaemus montrouzieri Mulsant	Coleoptera: Coccinellidae	Mealy bugs (pseudococcids) and aphids
Coleomegilla cubensis Casey	Coleoptera: Coccinellidae	Aphids, mites, and immature lepidoptera
Cycloneda sanguinea limbifer Casey	Coleoptera: Coccinellidae	Aphids and white flies
Chrysopa spp. Leach in Brewster	Neuroptera: Chrysopidae	Aphids, thrips, white flies, mites, and immature lepidoptera
Orius insidiosus Say	Hemiptera: Anthocoridae	Thrips, white flies, and mites
Zelus longipes L.	Hemiptera: Reduviidae	Lepidoptera larva

Source: Modified from Fuentes et al. (1998) and Massó (2007).

recently, the production of *Tsukamurella paurometabola* (Steinhaus) (Actinomycetales: Tsukamurellaceae) strain C-924 began to control nematodes.

The MBCA are registered and controlled in Cuba, unlike insects and entomophagous mites, which are not registered; but no single registry for these agents exists. The MBCA are on the Official List of Authorized Pesticides, published by the Central Registry of Pesticides, under the category of biological pesticides, together with the chemical-synthesis pesticides and those of natural origin (botanical extracts). Even though MBCA have been used for over 50 years in several areas, no specific regulation has been approved for their registry and control. In 2007, a joint resolution was approved in the Ministry of Agriculture and the Ministry of Public Health to approve and put into effect the Regulation for the Use of Formulated Pesticides. This resolution appears in an appendix titled "Procedures for the registry of biological pesticides" (MINSAP, 2007). An up-to-date list of registered MBCA appears in **Table 3**. The registry of agents formulated on the basis of *Trichoderma* (MINAG, 2016) is still pending.

Table 3: Registered microbial biological control agents produced in Cuba, updated in 2016. DOI: https://doi.org/10.1525/elementa.326.t3

Microorganism	Registered product	Organism/culture
Beauveria bassiana sensu lato (Bals.-Criv.) Vuill. (Hypocreales: Cordycipitaceae)	202/14 *Beauveria bassiana* L 10^8 conidium/mL, INISAV	*Lissorhoptrus brevirostris* (Suffrian) (Coleoptera: Curculionidae)/ rice (*Oryza sativa* L.) *Cylas formicarius* (Fabricius) (Coleoptera: Brentidae)/sweet potato (*Ipomoea batatas* (L.) Lam.) *Pachnaeus litus* (Germar) (Coleoptera: Curculionidae)/citrus *Cosmopolites sordidus* (Germar) Marshall, G.A.K. (Coleoptera: Curculionidae)/ banana
B. bassiana cepa MB-1	203/14 Bibisav –2 bait, 10^9 conidium/g, INISAV	*Atta insularis* Guérin-Méneville (Hymenoptera: Formicidae)
Metarhizium anisopliae sensu lato (Metsch.) Sorokin (Hypocreales: Clavicipitaceae)	169/15 *Metarhizium anisopliae* P 10^9 conidium/g, INISAV	*L. brevirostris*/rice *C. sordidus*/banana *Prosapia bicincta fraterna* (Say) (F.) (Hemiptera: Cercopidae) y *Mocis* sp./grasses
Lecanicillium lecanii (Zimm.) Zare & W. Gams (Hypocreales: Cordycipitaceae)	67/15 *Verticillium lecanii* 10^8conidios/mL, INISAV 168/15 *Verticillium lecanii* 10^9conidium/mL, INISAV	*Bemisia tabaci* (Gennadius) (*Hemiptera:* Aleyrodidae)/bean (*Phaseolus vulgaris* L.), vegetables and tomatoes (*Solanum lycopersicum* L.)
Pochonia chlamydosporia var. *catenulata* (Goddard) Zare & W. Gams (Hypocreales: Cordycipitaceae) cepa Vcc-108, IMI SD 187	189/14 KlamiC, CENSA, MES	*Meloidogyne* Göldi (Nematoda: Meloidogynidae)/organiponic vegetables, intensive gardens, and protected crops
Bacillus thuringiensis Berliner (Bacillales: Bacillaceae) var. *kurstaki*	196/14 *Bacillus thuringiensis* L 10^9esporas/ mL, INISAV	Lepidoptera larva/sweet potato, bean, cucurbits, tomato, grasses and fodder, tobacco, cassava (*Manihot esculenta* Crantz), soy (*Glycine max* (L.) Merr.), corn (*Zea mays* L.), potato (*Solanum tuberosum* L.) and pepper (*Capsicum annuum* L.) *Plutella xylostella* L. (Lepidoptera: Plutellidae)/cabbage (*Brassica oleracea* L. var. *capita*) and watercress (*Nasturtium officinale* R. Br.)
B. thuringiensis var. *israeliensis* serotype H-14	195/14 Bactivec SC 3 × 10^8 spores/mL, Labiofam	Mosquito larva
B. sphaericus cepa 2362	114/13 Griselesf 2362 SC, 3 × 10^9 spores/mL, Labiofam	Mosquito larva
Tsukamurella paurometabola (Steinhaus) (Actinomycetales: Tsukamurellaceae) strain C-924	057/12 HeberNem-L >5 × 10^{11} UFC/mL, CIGB Camagüey 115/13 HeberNem-S >3 × 10^{14} UFC/mL, CIGB Camagüey	Nematodes/banana, guava tree (*Psidium guajava* L.) and in vegetables in protected and semi-protected crops

Source: MINAG (2016).

Trichoderna Persoon (Ascomycota: Hypocreales: Hypocreaceae) is the most investigated and most used antagonist in the world. One of its most notable characteristics is its variety of antagonistic action modes (Martínez et al., 2013; Olmedo and Casas-Flores, 2014). *Trichoderma* is an especially important MBCA for Cuban agriculture since there are numerous alternatives in the country that reduce dependency on insecticides, either by substituting different BCA or through their removal from the registry (when their use is prohibited), or though deeper changes occurring in agroecosystem management that go quite a bit beyond managing harmful organisms.

The question of fungicides is very different since fewer alternatives exist to address diseases, in addition to the special and increasingly variable climatic conditions of a tropical country, and a growing tendency for conditions to continue that favor the appearance of epiphitoties. Research undertaken between 2005 and 2015 in seven provinces to evaluate trends in pesticide use, biological control agents, and other practices of managing pests showed that fungicides are the pesticides that are most widely applied. The number one product being consumed is Mancozeb (Pérez et al., 2010; Hernández and Pérez, 2012; Figueroa and Pérez, 2012). The use of Mancozeb poses risks for human health (PAN International, 2016), and there is little awareness of its risks.

In addition to the health risks, another problem merits analysis. The use of fungicides in Cuban agriculture needs to be reevaluated and viewed from a perspective different from what has prevailed until now. Such an evaluation needs to consider not only the control of phytopathogens, but also the fact that an excessive use of fungicides destroys the microorganisms that defend plants. How these defense mechanisms work has to do with biological control for conservation.

By analyzing this information, we can understand the importance of ongoing research on *Trichoderma* and the priority that should be given to its production. *Trichoderma* is applied yearly on more than a half-million hectares (Vázquez and Pérez, 2016). We should also establish new research objectives with other MBCA for which production technologies have been established, as is the case of *P. chlamidosporia* var. *catenulata* and *T. paurometabola*. Research on the antagonistic bacteria *T. paurometabola* strain C-924 has diversified and its potential as a BCA for phytopatogenic fungi is being determined (Marín et al., 2013).

Entomopathogenic nematodes

Within the set of organisms used as BCA, entomopathogenic nematodes (EPN) are the most recent. Documented EPN for Cuba belong to the *Steinernema* and *Heterorhabditis* genera. The latter appears most frequently and is the genus where the most-used strains are located, i.e., *Heterorhabditis indica* Poinar, Karunakar & David (Nematoda: Rhabditida: Heterorhabditidae) strain HI-24, *Heterorhabditis* spp. Strains CIAP-DEY-6, CIAP DEY-7, and *H. bacteriophora* strain HC1 (Rodríguez et al., 2012).

Twenty years elapsed from the time the first strains were isolated until rudimentary technology for mass production was in place. The *H. bacteriophora* species strain HC1 was the first to be used. This strain and the method for its reproduction were introduced in 1994 in the national program of biological control within the ex-Ministry of Sugar. By 2012, it was being reproduced in 33 CREEs (Rodríguez et al., 2012).

EPNs are recommended for the control of a numerous group of harmful organisms: *C. formicarius/*sweet potato, *S. frugiperda/*corn, *Diaphania hyalinata* L. (Lepidoptera: Pyralidae)*/*cucurbits, *C. sordidus/*banana, pseudococcids/coffee trees, pineapple, ornamentals, butterfly (*Hedychium coronarium* J. Koenig), *P. xylostella/*cabbage, lepidoptera/tomato, *L. brevirostris/*rice, *P. litus/*citrus, *A. insularis/*ornamentals, *H. virescens/*tobacco, *H. hampei/*coffee trees and scarab beetles/pineapple and guava trees (Rodríguez et al., 2011; Rodríguez et al., 2012). EPNs are not subject to registry.

Conservation biological control, what is least seen

CBC of natural enemies is defined as the modification of the environment or existing practices to protect and encourage natural enemies or other organisms to reduce the effect of pests (Eilenberg et al., 2001). The conservation of natural enemies is closely related to the design of the agroecosystem (Altieri and Nicholls, 2010) and the design is an essential element to take into account in the conversion of conventional agricultural systems to sustainable agricultural systems. Conversion is a gradual process that occurs in stages or levels. On large landholdings, it occurs on three levels, and on the scale of a country's entire food system, it occurs on five levels (Gliessman, 2015). The CBC strategy is closely tied to level 3, i.e., the redesign of agroecosystems to make them work based on new ecological processes.

Knowledge of how relationships between different components of the agroecosystem affect the ecosystem services provided by the biological control of pests allow designs to be built that enhance this service. The conversion that began in Cuba during the 1990s and still implemented at the country level (Funes and Vázquez, 2016) has produced changes in Cuba's agricultural outlook and thinking, which promotes better understanding of why it is necessary to continue conserving natural enemies.

Among the factors that have contributed to CBC in Cuba are:

1. The achievements and advances in ABC that laid a firm foundation for CBC of natural enemies;
2. The accumulation of positive experiences and new knowledge derived from the implementation of BC since the beginning of the 20th century;
3. The territorial programs of pest management that are integrated in BC;
4. The changes in land-management policies that led to an increase in the number of cooperatives, a downsizing of production units, and an increase in agrobiodiversity;
5. The adoption of BC by agricultural producers;
6. The adoption of agroecological management of pests in urban, suburban, and family agriculture; and
7. The application of BC with an ecosystems focus.

BC is not implemented as just another technology without considering the set of components that make up the agroecosystem and the way that these are interrelated. It is precisely where an ecosystems focus has prevailed in production units, systems, and regions that there has been the most progress. The steps taken in advancing toward CBC can be observed in the agroecosystems of urban, suburban, and family agriculture and in the production units organized in the Agroecological Movement of the National Association of Small Agricultural Producers (ANAP).

Even so, and in spite of the fact that the road to conservation has been built over solid foundations, we say that it is the least visible. Why the least visible? There are several explanations. First, the work of natural enemies in the countryside can go unnoticed even with the best experts, other than a small group of specialists who do research on this subject. Second, people may have information on how many kilos of a BCA, for example, *B. bassiana* or *Trichoderma* spp., are applied in a certain agroecosystem, or on how many hectares BCAs should be applied or released, but it is highly unlikely that they would have information regarding the populations of natural enemies that are present at any given moment in a sown field or locale, and even less likely if it is a parasitoid, predatory mite, or entomopathogenic nematode. This is so for aboveground organisms. For those that live underground, the chances are even slimmer, because it is an environment that has been scarcely studied and thus less is known about it.

Moreover, we must factor in the scarce assessment and dissemination of the goods and services offered by biological diversity and the fact that education and public awareness at all levels regarding conservation of biological diversity is still insufficient. This situation is clearly described in the Fifth National Report on the Convention on Biological Diversity of the Republic of Cuba (CITMA, 2014).

Cuban policy on biological diversity contributes to the goal of conservation of natural enemies. The "National Program on Biological Diversity" was presented in February 2016 for the years 2016 to 2020. This program took into account the adaptation in Cuba of the 20 Aichi Goals (international goals). Objective B, "Control the main threats to biological diversity and promote sustainable use," corresponds to Aichi Goal 4 and to Guideline 120 of Cuban economic policy. Action F states, "Undertake actions that contribute to the agroecological management of pests" (CITMA, 2016).

There are numerous practices that are a part of an applied CBC strategy (Pérez, 2007; Wyckhuys, 2013). These include notably the management of reservoirs of natural enemies by agricultural producers. In Cuba it is thought that reservoir management within small producers' conservation practices had its origin in the tradition of taking ant nests, of the *Pheidole megacephala* Fabricius (Hymenoptera: Formicidae) species, to sweet-potato fields to control *C. formicarius*, its principal pest. In the 1980s, the observation of this tradition stimulated interest in studying these predators (Pérez, 2007). The release of this predator from the producers' reservoirs on their land has been stable over time. Between 2004 and 2014, the predator was released yearly on more than 15,000 hectares (Vázquez and Pérez, 2016).

Other ways that reservoirs are being used today include: a) plant reservoirs are very common in urban, suburban, and family agroecosystems (INIFAT, 2018); and b) the application of a method of rustic breeding of coccinellids and two of their preferred prey, i.e., pseudococcids and aphids. Rustic insectariums are being used to reproduce the coccinellids *C. cubensis*, *C. sanguinea limbifer*, *Hippodamia convergens* Mulsant (Coleoptera: Coccinellidae), and *Chilocorus cacti* L. (Coleoptera: Coccinellidae) (Milán et al., 2010). In 2010, there were 118 insectariums in the provinces of Cienfuegos, Matanzas, Camagüey, Las Tunas, Granma, ex-City of Havana (today Havana), and ex-Havana (today Artemisa and Mayabeque.)

Conclusions

The contribution made by BC to the sustainability of the agri-food system is undeniable. This article has discussed evidence that supports this claim. Twenty-six years have passed since the transformation of Cuban agriculture began in search of sustainability. The events that have happened and the accumulated experience allow us to reflect on the lessons that were learned. The road to sustainability is far from being clear and well-charted; it was built slowly, step by step.

There are many questions to be answered but what is clear is the conviction that the solution to the problem of pests from an ecological standpoint does not lie in the quantity of BCA that are applied, nor in the number of agroecological practices that are undertaken. In the end, the secret lies in the optimization of ecosystem services, which sustain the necessary resources for ecosystems to work. We conclude by highlighting the idea that the biggest contribution of biological control to the agroecological management of pests is in the conservation of natural enemies and the gradual increase in biological diversity, which will move us closer to better health in the fields of human, animal, vegetable, and ecosystem wellbeing.

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The authors have no competing interests to declare.

Author contributions

- Contributed to conception and design: NPC, LM, LCJ
- Contributed to acquisition of data: NPC, LM, LCJ
- Contributed to analysis and interpretation of data: NPC, LM
- Drafted and/or revised the article: NPC
- Approved the submitted version for publication: NPC, LM, LCJ

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