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Insect biological control: a global perspective

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Abstract: The intentional use of biological control agents to manage arthropod pests dates back to as early as 304 AD, when Chinese farmers used weaver ants to manage citrus pests. Over time, biological control has evolved into distinct approaches: classical, augmentation, and conservation. Prior to the advent of pesticides, most insect pest management relied on natural and classical biological control. The most common strategy used at first, despite regional variations, was the importation of biological control agents. Nonetheless, due to issues with unintentional non-target impacts, numerous failures in the introduction, and longer periods required for implementation, augmentative and conservation approaches have become more frequently practiced. Additionally, growing demands from the government and the public for more sustainable farming, along with investments from private companies, have sped up the progress and use of augmentative biological control around the world. This extensive use of insect biological control agents and the ongoing development of new insights underscore the need for a thorough and up-to-date global review. We combine expertise from several world regions to address the unique historical, developmental, and regional challenges associated with augmentative insect biological control. From region to region, we observed differences in pest-natural enemy systems, places of implementation (greenhouse vs. field), type and level of investment (public vs. private), history of implementation, awareness of ecologically based strategies, and other factors. There are also many similarities, especially regarding the upcoming challenges in addressing the rising demand from the agricultural sector and climate change. These include producing and assessing the quality of biological control agents, establishing more biological control enterprises, improving the logistics of natural enemy transportation, making more use of native biological control agents in augmentative biological control, optimizing the utilization of mass-reared and resident biological control agents, increasing the application of ecologically based strategies at local and landscape levels, and promoting interdisciplinary collaborations. Taken together, the article offers an examination of the distinctive aspects of augmentative biological control programs and their associated challenges around the world.

Keywords: Integrated Pest Management (IPM), Mass rearing, Regulatory frameworks, Ecological intensification, native natural enemies, sustainable crop protection, entomopathogens, predators, parasitoids

1 Introduction

Humans have long studied and emulated nature to enhance food production and living conditions. Because heterotrophs consume other organisms, humans have been motivated to use one species to manage others that could pose a threat to us. In this context, biological control has long been used to manage agricultural pests worldwide.

Biological control has progressed from natural (no human intervention) to classical, conservation, and augmentative approaches. Prior to the introduction of synthetic pesticides, management of agricultural pests relied mostly on natural and classical biological control (Smith 1919; Waage & Greathead 1988). Conservation and augmentative approaches emerged in the early 20th century, although their foundational principles are older. The importation and large-scale production of biological control agents has enabled augmentative biological control. Nonetheless, the use of indigenous natural enemy species for biological control has grown in popularity due to the potential unintended consequences of exotic agents and restrictions to foreign genetic materials. Unintended consequences from releasing exotic natural enemies have led to the implementation of protocols for the importation and release of natural enemies (van Lenteren et al. 2006; Mason et al. 2021). Furthermore, restrictions on accessing foreign genetic material have emerged as a significant concern (Mason et al. 2021), and exchanging genetic material appears to be the next major issue for classical biological control.

Furthermore, government and public demand for more sustainable agriculture, along with private sector investment, have accelerated the development and use of augmentative biological control in agriculture. In 2024, the global biological control market was expected to be worth $6–7 billion. This market includes predators, parasitoids, and entomopathogens to control agricultural pests.

Despite increased global research and implementation of biological control, cultural and regional differences persist. Augmentative biological control is applied in greenhouses in temperate regions like Western Europe, Canada, and the US, while in tropical countries like Brazil, it is mostly used in open fields (Parra 2014). Augmentative biological control was pushed by government or public programs in China until recently. In other countries, augmentative biological control has been often driven by the private sector. Implementing biological control also varies by location due to growers' financial capacity. For example, some use resident biological control agents through conservation, while others use mass-reared biological control agents, particularly in locations where climate limits the natural enemy's persistence. Biological control is sometimes employed alone to manage pests, especially in organic farming, or as part of IPM programs.

Biological control can be added to IPM approaches and decision-making thresholds (Naranjo et al. 2015). IPM practitioners and researchers frequently advocate for the use of biological control over chemical control for pest management. The advent of more selective insecticides increases the potential for integrating chemical and biological control (Torres & Bueno 2018). Furthermore, broad-spectrum insecticide use has also decreased with *Bt* transgenic plants cultivation. This encourages the use of *Bt* plants and biological control agents in IPM, where *Bt* plants do not directly affect biological control agents (Romeis et al. 2019).

Many reviews have examined biological control. For instance, the recent work by Mason et al. (2021) addressed the history, impacts, and challenges of biological control of diverse target organisms with a variety of biological control agent taxa across various regions of the world. Nevertheless, a worldwide perspective on biological control of insect pests with natural enemies helps show the history, progress, and challenges of biological control. Here, our focus was on key regions of the world. Moreover, the continuous emergence of new insights underscores the need for a global point of view. Therefore, the goal was to assess and provide brief overviews of biological control programs in Africa (West, and South), China, Europe (France, Italy, Netherlands, Spain), Oceania (Australia, New Zealand and South Pacific Island countries and territories), North America (Canada, Mexico, USA), and South America (Argentina, Brazil, Chile, Colombia). We focus on augmentative biological control, while presenting (where appropriate) some background and trends in classical and conservation biological control. Due to space limitation, the review focused solely on predatory arthropods and parasitoids. Our primary objective was to offer an assessment of how biological control has evolved, with a particular emphasis on the distinctive history, development, and challenges associated with each region.

2 A perspective from Africa

2.1 A perspective from Southern Africa

The biological control of arthropod pests has a long history in southern Africa. In 1892 the lady beetle *Novius* (*Rodolia*) *cardinalis* (Mulsant) was introduced in South Africa to manage Australian cottony cushion scale (Witt et al. 2021). Since then, several highly successful classical biological control initiatives have been implemented, notably the biological control of the cassava mealybug, *Phenacoccus manihoti* Matile-Ferrero, utilizing the parasitoid *Apoanagyrus* (*Epidinocarsis*) *lopezi* (De Santis). This effort resulted in a total savings of US$9–20 billion, contributing to food security throughout the continent, and achieved a benefit–cost ratio of up to 430:1 (Neuenschwander 2010).

Augmentative biological control has had limited use in southern Africa. In the 1960s and 1970s, individual growers reared their own natural enemies on a small-scale, (Bedford et al. 1998), with commercial rearing and releasing of natural enemies only becoming commonplace in IPM programs in the late 1980s. Augmentative programs in southern Africa are largely confined to releases of parasitoid wasps, and some predators for the control of pests in high-value crops destined for export, most notably citrus, deciduous, and subtropical fruits. Augmentative control uses less than 20 registered biological control agents either locally reared in commercial insectaries or imported. In the region, augmentative control of arthropod pests is mostly implemented in South Africa, but there are programs in Zimbabwe, Zambia, Malawi, Swaziland, and Mozambique.

Mealybugs remain an important pest of citrus in southern Africa. Classical biological control of mealybugs using *Anagyrus vladimiri* (Triapitsyn) has played an important role against several species of mealybug worldwide (Franco et al. 2009). However, it has not been proven effective in suppressing the citrus mealybug, *Planococcus citri* (Risso) (Mendel et al. 1999). Regardless *A. vladimiri* is commercially reared in South Africa for the management of many mealybug species, including *P. citri, Pseudococcus ficus* Ben-Dov, *Pseudococcus maritimus* (Ehrhorn), *Pseudococcus viburni* Signoret and *Pseudococcus burnerea* (Brain)). Mommsen (2024) demonstrated that augmentative releases of *A. vladimiri* effectively suppressed the citrus mealybug, with early-season releases proving to be significantly more effective due to late build-up population of hyperparasitoids.

Another important biological control agent is the parasitoid *Aphytis lingnanensis* Compere. This parasitoid has been mass reared in South Africa by various insectaries for release in citrus crops since the early 2000s against red scale *Aonidiella aurantii* Maskell. However, unpublished research concluded that there was no evidence that augmentation of *A. lingnanensis* influenced the population dynamics of red scale. Furthermore, *Aphytis melinus* DeBach is now commercially available for augmentation in South Africa. This parasitoid was originally reared by an overseas insectary and imported into South Africa, although a South African insectary has also started rearing it. Extensive field trials by De Beer (2024) have shown that the augmentative releases of these two parasitoids were less effective at controlling red scale than the indigenous *Aphytis africanus* Quednau.

Trichogrammatoidea cryptophlebiae Nagaraja has been used for a long time in sub-tropical farming to help manage tortricids, such as *Thaumatotibia leucotreta* (Meyrick) (Bedford et al. 1998). The cost of the parasitoid is prohibitive. However, recently surplus egg sheets from the sterile insect program for *T. leucotreta* have been utilized to reduce the cost associated with *T. cryptophlebiae*, resulting in the treatment of over 40,000 hectares of subtropical crops annually. This illustrates the possibility for market elasticity when the price of the biocontrol agent is decreased.

Predator species are also used to control thrips and spider mites. For instance, the predatory bug *Orius laevigatus* (Fieber), phytoseiid mites *Amblyseius cucumeris* (Oudemans), *Amblyseius californicus* (McGregor), and *Phytoseiulus persimilis* Evans are also registered for use in southern Africa (Table 1S).

As mass-rearing technology has developed, arthropods have become more commercially viable as biological control agents. However, there are only a few arthropod natural enemies that can be economically mass-reared. One of the most significant barriers to producing natural enemies is the need to mass-produce their host or prey at low costs. Many commercially reared natural enemies are omnivorous predators, which may require plant availability. Developing artificial diets for parasitoids and predators could increase mass-rearing efficiency, becoming more cost-effective. However, artificial diets are frequently inferior to natural prey or hosts in terms of nutrition. As a result, parasitoids and predators raised on artificial diets often show weaker biological traits, making them less effective as biological control agents (Grenier & De Clercq 2003). Other problems for the commercial insect industry include making sure biological control agents stay vigorous during breeding, shipping, and release; not having enough published data on their effectiveness; and managing contamination and disease in the insect facility. We also need to streamline regulatory processes to enable registration within a realistic time limit. The cost of augmentative biological control is currently the most significant barrier to widespread adoption in southern Africa, and without government backing, subsistence agriculture will be unable to use it (Dougoud et al. 2018).

2.2 A perspective from Western Africa

In West Africa, agriculture is largely smallholder-based, yet pest infestations cause major crop losses, threatening food security (FAO 2019). Biological control offers a sustainable alternative to chemical pesticides, reducing environmental and health risks (Baker et al. 2020). Historically, classical biological control has played a vital role, with the introduction of *A. lopezi* reducing cassava mealybug (*P. manihoti*) populations by 80–90%, leading to a 30–50% yield increase (Gutierrez et al. 1988; Neuenschwander 2001). Similarly, *Habrobracon hebetor* Say has successfully controlled lepidopteran storage pests, reducing infestations by 60–85% (Goudiaby et al. 2019; Kabore et al. 2017).

More recently, conservation and augmentative biological control have gained traction, leveraging native natural enemies such as *Trichogramma* spp., *Eretmocerus* spp., and coccinellid beetles for sustainable pest management. Studies on fall armyworm [(*Spodoptera frugiperda* (J. E. Smith)] in maize have demonstrated the potential of these species in reducing pest pressure (Agboyi et al. 2020; Koffi et al. 2020). Push-pull technology, developed by International Centre of Insect Physiology and Ecology (ICIPE), is a promising approach that integrates repellent intercrops (*Desmodium*) and trap crops (Napier grass, *Pennisetum purpureum* Schum) to suppress maize stemborers while enhancing the conservation of parasitoids such as *C. flavipes* and *Cotesia sesamiae* (Cameron). Although adoption remains limited in the region, ongoing efforts aim to expand its use among smallholder farmers. Farmers using this approach report 50–80% less stemborer damage and 20–40% higher maize yields (Khan et al. 2008). Beyond push-pull, conservation biological control includes botanical pesticides and habitat management to support natural enemies. The promotion of neem-based pesticides and habitat management techniques help maintain populations of *Chrysoperla carnea* Stephens and *Hippodamia variegata* Goeze, reducing aphid infestations by 55–75% in vegetable systems (Elanchezhyana & Vinothkumar 2015). In cocoa and cashew plantations in Ghana and Côte d'Ivoire, flowering strips and agroforestry have increased native parasitoid populations such as *Anagyrus* spp., reducing mealybug infestations by 45–70% (Bisseleua et al. 2017; Sperber et al. 2004). Augmentative biological control involves the mass-rearing and targeted release of beneficial organisms. In Nigeria, augmentative releases of *H. hebetor* in grain storage facilities have cut post-harvest losses by 65–80% (Goudiaby et al. 2019; Kabore et al. 2017). Field trials in Benin and Burkina Faso with *Trichogramma* spp. have shown a 60–85% reduction in fall armyworm egg viability, leading to a 40–55% decrease in larval damage (Agboyi et al. 2020; Koffi et al. 2020). However, maintaining parasitoid populations during the off-season remains a challenge. Studies suggest that in addition to alternative hosts, some species can persist in crop residues, entering diapause until host populations increase (Sokame et al. 2019).

Despite its benefits, biological control adoption in West Africa faces several challenges. Limited research infrastructure and trained personnel hinder program development. Regulatory barriers, such as lengthy approval processes and inconsistent policies, delay commercialization. Climate variability, including temperature fluctuations and irregular rainfall, affects the establishment of biological control agents. Additionally, farmer awareness and adoption remain low, as many prefer chemical pesticides due to their immediate effects, highlighting the need for stronger extension services and training. Investing in research on native natural enemies can enhance their integration into agroecological pest management, reducing reliance on introduced species. Public-private partnerships can boost the commercialization of biological control products, ensuring sustainable access for farmers. Strengthening regional collaboration, farmer training and knowledge-sharing can further accelerate adoption. By addressing existing challenges and leveraging available opportunities, biological control can be widely adopted in agricultural systems in the region. Strengthening regional coordination and integrating biological control within agroecological approaches will be crucial for long-term success.

3 A perspective from Asia (China)

China has a long history of using biological control (Liu et al. 2014). The best example is the use of the weaver ants, *Oecophylla smaragdina* Fab., by farmers in southern China to manage citrus pests, a practice described as early as 304 AD (Cai et al. 2005). The parasitic tachinid flies of the silkworm, *Bombyx mori* L., were first mentioned in the Chinese literature around the same time. Due to the hidden habitats and complicated life cycles, the earliest record of insect parasitism dates back to 1096 AD, when the life cycle of a tachinid fly and egg deposition on silkworm caterpillars were described (Cai et al. 2005). This may have been the earliest record of insect parasitoids (van Lenteren 2005; Liu et al. 2014). The first Chinese record of the life cycle of a hymenopteran parasitoid dates from 1704 (Cai et al. 2005).

Detailed studies of insect parasitoids and biological control agents in China likely occurred in the 1920s, based on two publications on parasitoids of insect pests of mulberry trees (Liu et al. 2014). The first scientific papers focusing on biological control in China were published in the 1930s. More than 10 research papers focusing on parasitoid and ladybird beetles were published, and research laboratories were established (Wan et al. 2000). The first *Trichogramma* laboratory in China was established in Guangdong in 1958 (Zhao et al. 2020), and since then laboratories for other biological control agents have been established. Setting up a timeline of important events related to augmentative biological control in China, we highlight the establishment of the first national biological control agent research institute and quarantine laboratory in 1980 and 1984 (Yang 2015). As a result, the introduction of the first biological control agent in China occurred in 1984 (Yang 2015). Following the development of biological control, Guangdong Province developed China's first computer-controlled artificial egg card machine in the 1980s (Zhao et al. 2020), and Fujian established the first industrial breeding facility in the 1990s utilizing *Neoseiulus cucumeris* Oudemans. Furthermore, the first biological control biopesticide, *Trichogramma dendrolimi* Matsumura, with plasteopolyhedrovirus, was registered in 2010 (Hu et al. 2022), and in 2013 drones were first used to release *Trichogramma* (Li et al.).

Another milestone for mass rearing natural enemies was the use of indigenous insects, such as, the Chinese oak silkworm, *Antheraea pernyi* Guérin-Méneville. The use of factitious host made possible to rear biological control agents, such as, *T. dendrolimi* and *T. chilonis* Ishii (Zang et al. 2021), *Chouioia cunea* Yang (Yang et al. 2014), and *Anastatus fulloi* Sheng and Wang (Chen et al. 2022), which have become available for use at large scale (Table 2S).

To achieve sustainable agricultural development (Lu et al. 2017), biological control in China has been applied in agriculture, forestry, grassland, the edible mushroom industry, and storage activities (Ma et al. 2024). Close cooperation with international organizations (Zhang et al. 2015) has sustained basic research, product development, and translation of production to industrial scale.

Trichogramma spp., *Aphidius gifuensis* Ashmead, and *C. cunea* have been widely used (Table 2S). The development of diapause-promoting strategies has improved the shelf life of biological control agents (Zhang et al. 2014), making production and availability more efficient. From the 1980s to 2010s, the development of the biological control industry was mainly supported by government subsidies (Chen et al. 2015; Yang 2015), and products were applied by inundative release (Zhao et al. 2020). As of 2015, there are about 15 *Trichogramma*-related enterprises in China (Yang 2015). Using drone technology allowed rapid and precise release of biological control agents, such as *Trichogramma* in large areas (Li et al. 2013). The management of the invasive species *S. frugiperda* and *Phthorimaea* (= *Tuta*) *absoluta* Meyrick, has promoted international cooperation between China, CABI (Centre for Agriculture and Bioscience International), and The European Union (Zhang et al. 2015). Standardization of biological control products continues to progress; as of January 2023, 31 standards at all levels were established for the most widely used biological control product, *Trichogramma* spp., in China (Li et al. 2023).

There are various proposals about future development of biological control strategies, including whether to rely primarily on government subsidies or private investments. The screening of native biological control agents to manage invasive insects (Yang 2015b), and using models to predict invasion mechanisms are also current trends. There is a need to integrate pest monitoring, forecasting, computer networking, and information management to pest occurrence, invasion and establishment using remote sensing, global positioning systems, geographic information systems, artificial intelligence decision support systems, and computer-networked information management systems (Lu et al. 2017). The development of technologies such as packaging, storage and transportation (Chen 2010; Zhao et al. 2020) also needs to continue. Also, research should continue to explore the integration of biological control agents and pesticides when both are required to manage pests (Yang 2015b; Zhao et al. 2020).

There is a need to promote integrated multidisciplinary cooperation (Lu et al. 2017), and emphasize training of personnel (Chen 2010; Jiang et al. 2017). The integration of the internet indirectly benefits augmentative biological control by enhancing information delivery (Jiang et al. 2017) and promoting farmer-oriented popularization of biological control (Zhao et al. 2020), thereby facilitating the translation and implementation of new technologies.

4 A perspective from Europe (Spain, Italy, Netherlands, and France)

Although the concept of augmentative biological control has a long history in Europe [for a detailed exploration, consult van Lenteren (2012)], the era of this approach began in the early 20th century in southern European countries, such as, Italy, France, and Spain. Following the success of classical biological control in California with *N. cardinalis*, insectaries were established to introduce exotic biological control agents for targeting exotic pests. The first case was the release of the predator *N. cardinalis*, in Italy in 1901 (Viggiani 1994). In 1906, the parasitoid *Encarsia* (= *Prospaltella*) *berlesei* Berlese, was introduced to manage the white peach scale, *Pseudaulacaspis pentagona* (Berlese), in Italy (Nicoli 1997). In 1908, the lady beetle, *Rhyzobius lophantae* (Blaisdell), was introduced in Spain against diaspidid scales (Jacas et al.

2006). Since those initial introductions, and throughout the first three decades of the 20th century, numerous exotic species were introduced into Europe (Jacas et al. 2006; Nicoli 1997). The first cases of augmentative biological control in the field involved species of *Trichogramma* in France in the 1920s–1930s (Jourdheuil et al. 1991). It was also during this time that the use of biological control in greenhouses increased. In 1926, a tomato grower in England noticed black pupae among the normal white scales of the greenhouse whitefly, which were identified as *Encarsia formosa* Gahan (Speyer 1927). This led to the mass production and distribution to various nurseries in the United Kingdom and later to other countries, marking a significant turning point in pest management and agriculture. An important overview of the current status and challenges of biological control in the European Union was provided by Castella et al. (European Commission 2022), complemented by the work of the EPPO Panel on Biological Control, which addressed the safe use of biological control agents (Orlinski 2016).

After World War II, the use of biological control agents declined due to the introduction of chemical insecticides, which provided more convenient and effective management of greenhouse and field pests (Casida & Quistad 1998). However, the emergence of pesticide resistance in the late 1950s and 1960s renewed interest in biological control (DeBach 1974). Biological control use has increased in Europe, primarily because of organizations, such as, the International Organization for Biological Control (IOBC) (IOBC 2006), which promoted the use of biological control agents to manage pests. In protected crops, this facilitated the development and application of new biological control agents such as the predatory mite, *P. persimilis* in greenhouse horticultural crops (Bravenboer & Dossem 1962), against the two-spotted spider mite (van Lenteren & Woets 1988). In the 1980s, generalist phytoseiid predatory mites were mass-produced using bran and astigmatid mites as a prey source. Consequently, predatory mites could be mass-produced inexpensively and in large numbers (Ramakers & van Lieburg 1982). Predatory mites are used to manage thrips, spider mites and whiteflies (Table 3S). Since the 1990s, biological control in greenhouses has increased due to companies specializing in producing and marketing biological control agents (van Lenteren 2001, 2003, 2012). By the 21st century, biological control was the primary strategy used for protecting crops in Europe (van Lenteren et al. 2018, 2020). For example, in southeastern Spain, almost 30,000 hectares of horticultural greenhouses use biological control (Acebedo et al. 2022).

During the last decades of the 20th century, IPM programs were developed for various field crops. The IOBC facilitated knowledge exchange, supported young researchers, and developed IPM guidelines (https://iobc-wprs.org for further details). These IPM programs were mainly focused on the conservation of predatory mites and other biological control agents in fruit trees (Blommers 1994), such as, citrus (Jacas & Urbaneja 2010). Applying selective pesticides was also important for conservation (Desneux et al. 2007).

In the 1970s, there was a renewed interest in classical biological control by introducing parasitoids from the genus *Aphytis* against scale insects, and *Cales noacki* (Howard) to manage the woolly whitefly, *Aleurothrixus floccosus* (Maskell) (Nicoli 1997; Jacas et al. 2006). Until the late 1990s, the introduction of biological control agents continued to address emerging pests. However, introducing biological control agents resulted in controversy because of their potential impact on native biodiversity (Pedata & Hunter 1996) and issues associated with establishment in unwanted areas (Roy & Wajnberg 2008). This led to a reduction in use and the need to establish criteria to ensure safe introductions (Messing & Brodeur 2018). Increased international trade has triggered detection of exotic pests in agricultural systems (Skendžić et al. 2021). Many pests arrive without their biological control agents and are sometimes not managed by native natural enemies. This situation has led to the initiation of classical biological control programs, some of which have been successful, such as, the release of *Tamarixia dryi* (Waterson), for management of the African citrus psyllid, *Trioza erytreae* (Del Guercio), in citrus (Pérez-Rodríguez et al. 2024).

In recent trends, European biological control has experienced substantial growth and development, primarily in response to new agricultural and environmental demands. Europe has observed an expansion in the availability of biological control agents, including: parasitoids, predators, and entomopathogens (van Lenteren et al. 2018, 2020). Many biological control companies, including some multinationals, have expanded the availability of biological control agents (Table 3S). However, a change in biological control agent use has been observed over the past two decades, with the increasing utilization of generalist predators (Messelink et al. 2012). For example, even before the South American tomato pinworm, *P. absoluta* was detected in Europe, zoophytophagous mirids effectively managed tomato pests, including whiteflies, *Bemisia tabaci* (Gen.) and *Trialeurodes vaporariorum* West., as well as secondary pests (Calvo et al. 2012).

Technological advances have occurred in biological control, such as identifying pests and biological control agents through electronic traps with artificial vision (Ramalingam et al. 2020). These advances may provide support when making decisions associated with biological control (van Klink et al. 2022). Furthermore, molecular biology, proteomic and metabolic studies can now be used to optimize the diet of predators and enhance their breeding and field efficacy. Genetic breeding may be useful for selecting biological control agents to be better adapted to specific local conditions (Pérez-Hedo et al. 2017).

In Europe, there is pressure from the public and governments to reduce the use of synthetic pesticides, and use nature-based solutions to manage pests and diseases (European Commission 2017). European legislation produced guidelines to promote the reduction of pesticide use and encourage the adoption of biological control (European Commission 2022). In addition, there are issues related to producing pesticide residue-free fruits and vegetables by the retail industry (Carrasco Cabrera et al. 2024). Consequently, research projects and studies on optimizing biological control have become more relevant.

Despite the advances in biological control use in Europe over the last 20 years, there are challenges that could undermine its effectiveness. However, these challenges also provide opportunities to innovate and advance biological control. Climate change affects the dynamics of pests by altering their life cycles and expanding geographic ranges, which may compromise the effectiveness of biological control agents in the field (Furlong & Zalucki 2017). Climate change requires the development of biological control agents that can adapt to change weather patterns and still manage pest populations below plant damaging levels (Lamichhane et al. 2015).

Current research in biological control in Europe mainly focuses on optimizing biological control agents through advanced breeding, formulation, conservation, and application methods that ensure effective pest management in diverse environmental conditions. The biological control market is growing, but there are challenges, such as competition from pesticide companies and diverse regulations. The response to introduction of pest or disease usually involves applying pesticides. The use of pesticides can have unintended consequences that disrupt existing biological control agents (Johnson et al. 2020). Hence, resilient biological control agents are needed to help manage invasive pests. Governments have to expedite these processes and provide incentives for research and development in biological control.

Further challenges include: (i) Biological control in Europe faces challenges from invasive pest species, which can impact local ecosystems and crop yields. (ii) The economic viability of biological control, particularly in minor crops, is a challenge. These crops have less funding for pest management strategies than major crops. Developing cost-effective augmentative biological control solutions focused on small and medium-sized enterprises that can be quickly adopted is crucial. (iii) Although results have been achieved in training farmers and technicians, particularly in augmentative biological control, there are issues associated with skills and knowledge among practitioners regarding the implementation of conservation biological control strategies. Improving training and resources for farmers and pest managers on obtaining, releasing, and conserving biological control agents could enhance the success of augmentative biological control.

Addressing these challenges requires a coordinated effort among researchers, industry stakeholders, and policymakers to advance the development and implementation of effective biological control strategies in Europe.

5 A perspective from North America

5.1 A perspective from Canada

Canada was one of the first countries to implement classical biological control, with releases of biological control agents initiated in the late 1800s and early 1900s (Glen 1956). Since then, at least 229 species of imported biological control agents have been released to target 76 pest species in agricultural, forest, and urban settings (McClay et al. 2021). Success rates of these introductions are estimated at about 20% (McClay et al. 2021). Due to more stringent standards for host specificity of imported biological control agents, the number of imported and released biological control agents has declined (McClay et al. 2021). However, a national collaborative network of government and university researchers continues to conduct research advancing the implementation of classical biological control programs (Vankosky & Martel 2024).

Successful examples of classical biological control in Canada include the introduction of a parasitoid targeting the beetle *Lilioceris lilii* (Scopoli) (Cappuccino et al. 2013), and the release of a parasitoid against the moth *Acrolepiopsis assectella* (Zeller) (Mason et al. 2013). Foreign exploration and sourcing of biological control agents relies on collaboration with researchers from the international organization CABI, while research and petitioning for first-time biological control agent releases are often coordinated with colleagues from the United States Department of Agriculture and Agricultural Research Service (USDA-ARS). Guidelines for the importation and release of classical biological control agents are harmonized between Canada and other North American countries through the North American Plant Protection Organization, and the scientific review of petitions to release biological control agents involves cooperation between Canada, the USA, and Mexico (Mason et al. 2017).

A major issue in classical biological control in Canada, as with other areas of the world (Weber et al. 2021), is the unintentional introduction (or spread from adjacent countries) of non-native biological control agents (Abram et al. 2019, 2020). Because Canada is geographically vast (>9.9 million km^2), ecologically diverse [9 level 1 ecoregions (CEC 1997)], and contains geographic barriers to insect dispersal (e.g., the Rocky Mountains), the redistribution of biological control agents within the country can share many of the same scientific considerations. The redistribution of the parasitoid fly *Istocheta aldrichi* Mesnil, from Eastern Canada to British Columbia for biological control of the Japanese beetle, *Popillia japonica* Newman, in 2023 (Makovetski & Abram 2024) and the parasitoid, *Ganaspis kimorum* Buffington, from British Columbia to Ontario in 2024 (P. Abram, pers. obs.) are pilot projects for the development of responsible, science-based redistribution practices.

In Canada, augmentative biological control programs targeting at least 32 pest species have increased populations of biological control agents in areas where they were absent or present in low numbers (MacQuarrie et al. 2013, 2016). For example, the release of the native parasitoid, *Trichogramma minutum* Riley, to manage *Choristoneura fumiferana* (Clemens), was successful (Smith 1996). A more recent augmentative biological control program targeted the emerald ash borer, *Agrilus planipennis* Fairmaire (Gaudon & Smith 2020), that has killed tens of millions of ash trees (Cappaert et al. 2005). The initial results are promising (Butler et al. 2022) (Table 4S).

The increase of protected crop production in Canada over the past century has been followed by increases in the incidence and risk posed by pest outbreaks. In the early 20th century, the major insect pest in greenhouses was the greenhouse whitefly, was managed by the parasitoid, *E. formosa*, but its use decreased with the development of insecticides (Baird 1935; McClanahan 1970). In the 1970s, a partnership between Agriculture and Agri-Food Canada and the Ontario Greenhouse Vegetable Producers Marketing Board resulted in two spin-off companies in eastern and western Canada and the mass production of *E. formosa*, as well as the predatory mite, *P. persimilis* (Shipp et al. 2007). The Canadian greenhouse industry is serviced by a growing biological control agent market, which now includes nine Canadian and six multinational suppliers (McCreary 2024) (Table 4S). The industry supplies a diversity of biological control agents targeting at least 30 pest species (OMAFRA 2024). The primary biological control agents purchased are *P. persimilis* and, more recently, *Stratiolaelaps scimitus* (David Spencer, Applied Bio-Nomics Ltd., pers. comm.). While a significant proportion of biological control agents are exotic species, there is increasing interest in native biological control agents. For instance, several native species are available as part of a partnership between Applied Bio-Nomics Ltd. and the Laboratoire de Lutte Biologique (UQAM, Quebec) and the Vineland Research and Innovation Centre (Ontario). Several biological control agents have been released to manage greenhouse pests. For example, the native hoverfly, *Eupeodes americanus* (Wied.), is a predator of the aphids, *Myzus persicae* Sulzer and *Aphis gossypii* (Glover), and they are used with banker plants or pupal releases (Gonzalez et al. 2024). The parasitoid, *Jaliscoa hunteri* Crawford, from Mexico, but now found in Canada, shows promise for management of the weevil, *Anthonomus eugenii* Cano, in pepper (Leo et al. 2024). The native hemipteran, *Nabis americoferus* Carayon, is used to manage several pests in greenhouses, including *M. persicae, T. vaporariorum, Frankliniella occidentalis* (Pergande), and *Lygus lineolaris* (Palisot de Beauvois) (Saito et al. 2023b; Dumont et al. 2023). Some recently developed biological control agents include *Dicyphus famelicus* (Uhler) and *D. discrepans* Knight (Demers 2024) and the predatory mite, *Anystis baccarum* L. (Saito & Brownbridge 2022, Saito et al. 2023a).

Habitat conservation has recently received attention in Canada. For example, studies at the landscape scale have associated increased crop richness and diversity with reductions of specialist pest populations, such as, *Aphis glycines* Matsumura and *Oulema melanopus* (L.) (Almdal & Costamagna 2023). The parasitism of *O. melanopus* has increased by the introduction of the parasitoid, *Tetrastichus julis* (Walker). The presence of nearby woodlands, some crops, and greater field edge density increased predator abundance, functional diversity, and predation in different regions of Canada (Kheirodin et al. 2022; Almdal & Costamagna 2023). Furthermore, studies with bidirectional Malaise traps demonstrated the importance of predator movement from adjacent crops and habitats on, aphid suppression in soybean (Almdal & Costamagna 2023). In Alberta, the density of generalist ground predators is higher in seminatural habitats later in the season, suggesting that these habitats function as overwintering areas and sources of predators in the next season (Robinson et al. 2021), and in Manitoba, floral strips in field borders increased carabid abundance (Killewald et al. 2024). These studies demonstrated that habitat manipulation can enhance pest suppression by conservation biological control.

In conclusion, classical biological control is regularly practiced in Canada despite comprehensive regulations, which have resulted in a reduced rate of biological control agent introductions. Augmentative biological control is an important part of pest management in protected agriculture in Canada. The introduction of new biological control agents for commercial use is now focused on native species. A major challenge for the remaining Canadian producers of biological control agents is the trend toward consolidation with the dominance of multi-national producers.

5.2 A perspective from Mexico

The record of biological control in Mexico began in 1902, with the introduction of the Myoktanine virus to manage the field rat, *Rattus sordidus* (Gould) (Herrera et al. 1902). Currently, about 100 entomophagous species have been imported into Mexico for pest management. Establishing facilities for mass rearing beneficial organisms began in the 1960s, and today Mexico is a reference in augmentative biological control (Arredondo-Bernal & González-Cabrera 2020; Arredondo-Bernal & Rodríguez-Vélez 2020). Specific information on 43 cases of classical and augmentative biological control in Mexico have been revised by Arredondo-Bernal & Rodríguez del Bosque (2008; 2015).

Globally, Mexico is one of main producers of plant-based foods on 110.3 million hectares. Agriculture occupies 29.4% of the area, and it frequently exports crops such as avocados, tomatoes, and berries (Arredondo-Bernal & Rodríguez-Vélez 2020). The climate conditions allow for year-round production with increased value among global food industry (Arredondo-Bernal & Rodríguez-Vélez 2020).

Mexico has 81 laboratories for producing beneficial organisms; 49 are insectaries that produce 37 species of entomophages, which along with imported species result in 75 species used for managing pests in staple, industrial, fruit, vegetable, and forestry crops, as well as in the berries and ornamentals industries (SENASICA 2024) (Table 5S). The area covered by biological control in the field is not clear, but it is known that this technology protects over 11.9 million hectares of crops (Arredondo-Bernal & Rodríguez-Vélez 2020). The primary biological control agents produced are *Trichogramma* spp., which are used to manage pests in corn, sugarcane, and vegetables. In addition, biological control agents are produced for managing whiteflies, sugarcane borers, corn earworms, the Heliothinae complex, aphids, scales, thrips, mealybugs, psyllids, phytophagous mites, and flies. Furthermore, the federal government, along with some states, has production laboratories that provide free-of-charge biological control agents. In addition, the industry and research centers are looking for new biological control agents for pests such as the pepper weevil, mealybugs, tephritid fruit flies, corn earworms, and greenhouse pests (Table 5S).

In 1986, the Mexican government created 21 insectaries for reproduction of biological control agents, but starting in 1990, they were transferred to farmer organizations for operation and management. In addition, in that year, interest in commercial biological control increased, and by 1991, there were 43 laboratories.

Protected agriculture has experienced significant growth, especially for crops such as tomato, cucumber, bell pepper, eggplant, strawberry, raspberry, blackberry, and ornamental plants; which require beneficial organisms to address various phytosanitary problems. In 2022, the planted area was 86,796 hectares, including shade netting, shade houses, macrotunnels, and greenhouses (https://www.gob.mx/siap/documentos/agricultura-protegida-200653). Currently, augmentative biological control is present in over 14,000 hectares of greenhouse crops (Julio Velázquez, Koppert Mexico, personal communication); just in 2018, over 2,978 million entomophagous insects and mites were imported (Arredondo-Bernal & González-Cabrera 2020). It is worth mentioning that there is a lack of beneficial organisms that complement the action of the existing ones, thereby driving the search for new alternatives. Additionally, an increase in demand is expected in the short term, which will generate market opportunities for the biological control industry.

The Federal Plant Health Law and its Regulation (DOF 2016, 2022) established that the government must regulate the safe use of biological control to manage crop pests. This entails monitoring the movement of species collected in the field and regulating the importation of biological control agents. Certificates are also granted, at the industry's request, to ensure the origin and biological purity of beneficial organisms intended for export. This law aims to protect agriculture and the environment by limiting the introduction of unwanted species and encourages the use of this technology by simplifying the importation process for 58 beneficial species of insects (RSPM 26 2015). Additionally, the Federal Government carries out biological control programs in phytosanitary campaigns supported by the National Biological Control Center. This center develops, validates, and transfers technology for its application in biological control (https://www.gob.mx/senasica/acciones-y-programas/centro-nacional-de-referencia-de-control-biologico-103097); with three recent and emblematic cases being the mass production of *Anagyrus callidus* Triapitsyn, Andreason & Perring, *Tamarixia radiata* (Waterston), and *Trichopria drosophilae* Perkins (González-Cabrera et al. 2021).

A major challenge has been to avoid new pest arrivals. Mexico has 14 trade agreements with over 50 countries/nations, which represent risks of introducing pests. For example, the ambrosia beetle *Xyleborus glabratus* Eichhoff and the polyphagous shot hole borer *Euwallacea fornicates* (Eichhoff), already present in North America, is a constant threat with the potential to affect over 250,000 hectares of avocado. The tomato pinworm, *P. absoluta*, already present in South America, jeopardizes more than 50,000 hectares of tomato and nearly 70,000 hectares of potato. On the other hand, *Drosophila suzukii* (Matsamura) affects crops such as blueberries, raspberries, blackberries, strawberries, cherries, and grapes, although it has been managed through trapping, cultural practices, and biological control (Cárdenas & Chavero 2014; González-Cabrera 2021). Other threats include the red palm weevil, *Rhynchophorus ferrugineus* (Olivier), the European grapevine moth, *Lobesia botrana* (Denis & Schiffermüller), and the old-world bollworm, *Helicoverpa armigera* (Hübner), none of which are currently present in Mexico. Currently, there are projects for the development of preventive technology for the use of mirids against *Phthorimaea* and *Helicoverpa*.

Although biological control by entomophagous arthropods has a history spanning over a century, it has experienced a marked resurgence over the past three decades (Rodríguez-del-Bosque et al. 2015; Aluja et al. 2020). Mexico has infrastructure for this practice, including specialized laboratories and commercial suppliers, with participation from the government sector, private initiative, and academic institutions (Williams et al. 2013). Although there are biological control agents available for most greenhouse pests, some of them do not have the desired impact, and native species are still being sought as an alternative. Moreover, Mexico is the center of origin for many crops such as maize, chili peppers, avocado, prickly pear, cocoa, beans, squash, cotton, mamey, among others. This represents an opportunity for the search for biological control agents of pests that affect these crops, either for local use through augmentative and conservation biological control, or for classical biological control in other countries that could import such natural enemies (Lomeli-Flores et al. 2023).

An approach that prioritizes the exploration of native species' potential has been adopted, with the goal of integrating environmental sustainability and social benefits. We are confident that the development of augmentative biological control will continue to advance, driven by the growing demand from export markets for low-residue, pesticide-reduced agricultural products, as well as by increasing interest within the domestic market.

5.3 A perspective from the United States of America

The use of biological control is increasing in greenhouse production systems throughout the United States of America (USA) primarily because of two factors: 1) resistance to pesticides (e.g. insecticides and miticides), and 2) no new active ingredients introduced into the marketplace (Van Driesche & Heinz 2004a; Cloyd 2016). The biological control agents used in greenhouse production systems include predatory mites, predatory bugs, lady beetles, rove beetles, green lacewings, midges, parasitoids, and entomopathogenic nematodes (Osborne et al. 2004; Cloyd 2016). The major targets of biological control agents are the green peach aphid, *M. persicae* (Sulzer) cotton aphid, *A. gossypii*, greenhouse whitefly, *T. vaporariorum*, sweetpotato whitefly, *B. tabaci*, twospotted spider mite, *Tetranychus urticae* Koch, fungus gnats, *Bradysia* spp., and Western flower thrips, *F. occidentalis* (van Lenteren & Woets 1988, Osborne et al. 2004). The biological control agents commercially available from distributors and/or suppliers for use in greenhouse production systems in the USA are presented in Table 6S.

Implementing a biological control program in greenhouse production systems in the USA presents a number of challenges including: 1) Costs of biological control agents and labor associated with releasing them; 2) Determining the quality of biological control agents; 3) Issues related to current greenhouse production systems.

Although overcoming these challenges is not insurmountable, the ability to do so require an understanding of the fundamentals affiliated with using biological control agents to manage greenhouse insect and/or mite pest populations below plant damaging levels. Therefore, this article will discuss some of these challenges in detail.

Costs of implementing a biological control program. The costs of implementing a biological control program in the USA may be more expensive than using pesticides (Stevens et al. 2000; Van Driesche & Heinz 2004b). Consequently, there is a perception by users that biological control is more costly than applying pesticides. However, the costs of releasing biological control agents, in some cases, may be less expensive than applying pesticides (van Lenteren 1992; Van Driesche & Heinz 2004b). Regardless, the direct costs affiliated with biological control are similar to using pesticides including the labor required to apply the product (Williams & Cloyd 2005). The main direct costs of implementing an augmentative biological control program are related to the purchase of biological control agents and labor involved in applying/releasing biological control agents; especially if multiple releases are required (Scopes 1969).

A major expense associated with purchasing biological control agents is the shipping/freight costs because they must be shipped overnight to ensure survival upon receipt. The shipping/freight costs can be higher than the actual biological control agents (Williams & Cloyd 2005), which can be a deterrent in implementing a biological control program, particularly when shipments are scheduled to arrive regularly (e.g., every week).

The labor required to release biological control agents can vary depending on the method used. For example, whitefly parasitoids are applied as release cards that contain parasitized whitefly pupae in which parasitoid adults will emerge. The release cards are placed among a crop throughout a greenhouse production area. Predatory mites are available in containers mixed with a carrier (e.g., bran or vermiculite) or sachets (slow-release bags) that contain eggs, immatures (larvae and nymphs), and adults (Midthassel et al. 2014; Buitenhuis et al. 2014). These formulations are distributed or placed throughout a greenhouse production area (Williams & Cloyd 2005; Midthassel et al. 2014; Cloyd 2024). However, using mechanical blowers to apply/release predatory mites can lower labor costs (Opit et al. 2005; Williams & Cloyd 2005).

The quality of biological control agents. An important factor when using biological control is to ensure that biological control agents received from suppliers are alive and functional prior to release (van Lenteren & Nicoli 2004; Cloyd 2016). Biological control agents of inferior quality can result in inadequate management of pest populations, thus leading to a false assumption that biological control is not effective (O'Neil et al. 1998; Lundgren & Heimpel 2003). Therefore, the success of a biological control program is contingent on the quality of the biological control agents released (van Lenteren et al. 1980). In addition, distributors and/or suppliers must ensure proper packaging of biological control agents to provide protection from exposure to extremes in temperature and relative humidity (van Lenteren & Woets 1988; Van Driesche & Heinz 2004b).

The issue of quality may not be related to the distributor and/or supplier but instead may be affiliated with what happens during shipping, which is beyond the control of the distributor and/or supplier (Waddington 1993). For instance, exposure to unfavorable environmental physical conditions may compromise the quality of biological control agents (Cloyd 2016). Consequently, the quality of purchased biological control agents must be assessed before releasing or applying into greenhouse production systems (Cloyd 2016). The quality of biological control agents can vary depending on packaging of products from commercial distributors and/or suppliers (Fernández & Nentwig 1997). Furthermore, the quality of the same biological control agent (e.g., longevity, size, fecundity, etc.) may differ depending on the commercial distributor (Herrick & Cloyd 2022). Publications are available that provide guidelines on how to conduct quality assessments of commercially available biological control agents (van Lenteren et al. 2003; Buitenhuis 2017) that can be utilized when assessing the quality of purchased biological control agents.

Difficulty integrating pesticides with biological control agents. Another challenge is integrating pesticides with biological control agents in greenhouse production systems. In some cases, biological control agents alone may not provide acceptable management of the pest populations (Veanman 1992). Therefore, insecticides and miticides may be required to manage pest populations (Stark & Banks 2003; Stark et al. 2007).

There are issues associated with integrating pesticides with biological control agents, as the direct, indirect, and sublethal effects of pesticides on biological control agents (Gradish et al. 2011; Herrick & Cloyd 2017; for a thorough review see Desneux et al. 2007). Any direct and/or indirect effects can compromise the ability of biological control agents to manage insect and/or mite pest populations below plant damaging levels (Cloyd 2012).

In general, newer synthetic pesticides have less direct and/or indirect effects than conventional broad-spectrum ones (Cloyd 2006). However, biopesticides based on entomopathogenic fungi can directly and/or indirectly affect particular biological control agents (Cloyd 2006; Roy & Cottrell 2008). Studies demonstrate that pesticides can vary in how they directly and/or indirectly affect certain biological control agents including the rove beetle, *Dalotia coriaria* (Kraatz) and insidious flower bug, *Orius insidiosus* (Say) (Herrick & Cloyd 2017; Cloyd & Herrick 2018). Due to the complexity of integrating pesticides with biological control agents, the strategy may be to use biological control or pesticides to manage insect and/or mite pest populations.

Issues related to current greenhouse production systems. A final challenge associated with using biological control agents is the current greenhouse production system in the USA. Greenhouse production systems in the USA are typically multi-cropping systems (polycultures), where many different types of horticultural crops (e.g., bedding plants and vegetables) are grown simultaneously in close proximity with continuous crop production year-round (van Lenteren & Woets 1988; Osborne & Oetting 1989). Multi-cropping systems can affect the success of biological control because of the simultaneous occurrence of different pest species (Cloyd 2016; Parrella & Lewis 2017). Hence, multi-cropping systems can increase the difficulty and subsequent costs of using biological control agents (van Lenteren et al. 1980), which can reduce implementing a biological control program.

Considerations for the USA biological control advance. There are several challenges in implementing a successful biological control program in greenhouse production systems in the USA that must be taken into consideration as pointed out above. Overcoming these challenges requires understanding the fundamentals associated with using biological control agents to manage greenhouse insect and/or mite pest populations below plant damaging levels. In addition, funding is needed to support scientific studies designed to understand the biology and ecology of new and currently available biological control agents, which will increase the knowledge and subsequent use of biological control to manage insect and/or mite pest populations in greenhouse production systems in the USA.

6 A perspective from Oceania (Australia, New Zealand and South Pacific Island countries and territories)

Australia played a key role in the development of modern classical biological control by supplying the biological control agents for release against the invasive cottony cushion scale, *Icerya purchasii* Maskell in California in the 1880s. This important contribution was soon followed in the early 1900s by the wanton importation and release of numerous parasitoids in Australia by Compere. Since then, interest in biological control has waxed and waned, depending on the invasive pest species and government funding for research (Zalucki 2015). Although strict guidelines and protocols have been developed and improved over time (see for example Avila et al. 2023), public concern over the “cane toad syndrome” (Zalucki 2015) persist, and biological control programs require considerable engagement with all stakeholders.

The greatest efforts in biological control research and implementation have occurred in Australia and New Zealand, although there has been substantial activity in many Pacific Island countries and territories (PICTs) (Fig. 1S). In these smaller countries biological control programs, which are often funded by international donors, are typically based on successful introductions elsewhere (Day et al. 2021), ranging from 32% to 76% (Fig. 1S). In New Zealand, a national database records all biological control endeavors (Better Border Biosecurity 2024), but the latest comprehensive reviews of arthropod biological control in Australia (Waterhouse & Sands 2001) and PICTs (Waterhouse & Norris 1987) require revision and updating. Estimates of target species managed following biological control agent establishment are highly variable, ranging from 0–51% (Fig. 1S), but the impact of established biological control agents on target pests is rarely tested (Furlong & Zalucki 2010; Zalucki et al. 2015). Nevertheless, there have been some successes leading to major improvements in pest management, and overall cost-benefit outcomes have been estimated to be 607:1 (Waterhouse & Sands 2001).

In Australia, successful biological control programs have been mounted against different whitefly species (De Barro & Coombs 2009; Lambkin & Zalucki 2010), and green vegetable bugs (Coombs & Sands 2000). However, one of the better-documented success stories is the biological control of scale insects in citrus (Zalucki et al. 2009). Many of the major insect pest species of citrus production in Australia are exotic scale insects including white wax scale (*Ceroplastes* *destructor* Newstead), California red scale (*A. aurantia*), circular black scale (*Chrysomphalus aonidum* L.), pink wax scale (*Ceroplastes rubens* Maskell), and white louse scale (*Unaspis citri* (Comstock)). The successful management of these insect pests using introduced parasitoids (Smith 1986; Smith & Papacek 1995) as well as augmentative biological control against the dominant scale insect pests (Smith et al. 1997), provided the groundwork for practical integrated pest management (IPM). In the absence of disruptive insecticides these biological control agents can provide effective suppression of target pest species, and the reduced insecticide input has resulted in greater mortality of other minor pests by natural enemies (Papacek & Smith 1989). The production of various biological control agents by commercial operators, initially for citrus pests, led to the development of an industry of biological control suppliers in Australia, which included nine commercial companies between 2002 and 2010 (Begum et al. 2017). Today, only four independent suppliers offer arthropod biological control agents (Table 7S). Although 33 different biological control agents are available, 73% are available from only a single supplier, 18% are available from two suppliers and only three biological control agents (all predatory mites) are available from three suppliers (Table 7S). This has implications on the sustainability of the industry and the practice of augmentative biological control in Australia as transport of biological control agents is costly and time consuming.

The adoption of IPM in field crops has allowed classical biological control agents to fulfil their potential, when introduced into climates to which they are adapted. For example, in 1936, the diamondback moth *Plutella xylostella* L. larval-pupal parasitoid *Diadegma semiclausum* Hellén was imported from the United Kingdom to the South Island of New Zealand (Hardy 1938). The parasitoid established and provided the source material for *D. semiclausum* introductions into Asia, Africa, and elsewhere in Oceania (Furlong et al. 2013), including Australia where the establishment of the parasitoid took place late 1940s (Wilson 1960). The parasitoid contributed to diamondback moth management in Australia until the widespread use of broad-spectrum insecticides in the late 1980s and early 1990s resulting in increased pest populations that were resistant to insecticides (Heisswolf et al. 1997). Consequently, in southeast Queensland, an IPM approach that advocated the use of selective insecticides, especially *Bacillus thuringiensis* (*Bt*), and a summer production break was implemented (Heisswolf et al. 1997). Growers who adopted the practices experienced benefits from *D. semiclausum* and other introduced and native biological control agents (Furlong & Zalucki 2007; Furlong et al. 2004ab). *Bt* products have been replaced by other selective insecticides such as spinosad, indoxacarb, and chlorantraniliprole, which are less disruptive to biological control agents of the diamondback moth (Chen et al. 2008), and market forces have resulted in the abandonment of the production break. Hence, biological control agents have declined, and pest problems have increased. Following the successful biological control of diamondback moth in New Zealand, *D. semiclausum* and several other parasitoids, *Cotesia vestalis* Halliday, *Oomyzus sokolowksii* (Kurdjumov), and *Diadromus collaris* (Gravenhorst), were introduced to PICTs including Cook Islands, Fiji, Papua New Guinea, Samoa and Tonga from the 1940s through the 1980s (Waterhouse & Norris 1987). Some introductions resulted in successful establishment (Waterhouse & Norris 1987), but none were assessed for their impact on pest populations. Following the documented biological control success against diamondback moth by *D. semiclausum* in Malaysia (Ooi 1992), the German Agency for Technological Cooperation (GTZ) funded a regional biological control project to release *D. semiclausum* into Fiji, Papua New Guinea, Tonga, and Samoa. The parasitoid only established in Papua New Guinea, but only at altitudes above 1600 m (Saucke et al. 2000), likely reflecting its northern Palaearctic origins and the unsuitability of the climate at release locations elsewhere in the region.

There has been growth in the research effort on quantifying the interaction of pests and biological control agents that occurs on landscape scales and how they impact pest population dynamics and management (Furlong et al. 2008; Zalucki et al. 2015; Akter et al. 2023). A key area that requires attention is the implicit, often naïve, assumption that more generalist predators in a field, or nearby, leads to greater management of pests. In practice, however, most predators are not generalists, as determined by molecular investigation of gut contents (Furlong et al. 2014; Furlong 2015). The problem is also related to translating sample estimates of natural enemy abundance into pest mortality (Nagy et al. 2020). Simply assessing natural enemy biodiversity and trophic relationships does not provide practical information to producers (Perovic et al. 2021). Another challenge is realistic assessments of climate change impacts not just on the pests and biological control agents, but also their interactions (Furlong & Zalucki 2017). This is essential as we navigate the changing conditions under which established biological control agents are required to function and for effective future planning appropriate biological control agents for release against emerging insect pests.

7 A perspective from South America

Biological control has gained popularity in South America. The industry investments in biological inputs and public demand for safer, more sustainable food products have been driving this interest (Lopes et al. 2023; Parra 2023). Marketing efforts and the belief that boosting biological control agents can solve issues caused by synthetic insecticides have further highlighted biological control. Until the 1970s, biological control in South America primarily focused on the importation of biological control agents (van Lenteren & Bueno 2003). The implementation of augmentative biological control only appears later in the 1970s in countries such as Bolivia, Peru, and Brazil (Hagen & Franz 1973; Parra 2014). The establishment of entomology departments and graduate programs in universities between 1960s and 1970s also played a crucial role in advancing biological control in South America.

Several South America countries now use augmentative biological control. However, the level of adoption and the number of biological control agents available vary per country. Factors such as public and private investment, farmer practices, crop types, pest and natural enemy species, and government regulations on bioinputs cause discrepancies across countries (Peñalver-Cruz et al. 2019; Parra 2023).

Industrial farming systems are currently more inclined to use augmentative biological control due to their greater financial resources. Conversely, smallholders in South America may depend more on conservation or natural biological control strategies due to the high costs or limited availability of mass-reared biological control agents (Peñalver-Cruz et al. 2019; Blassioli-Moraes et al. 2022).

Despite augmentative biological control research and application in South America have advanced, many challenges remain. Augmentative biological control in the tropics targets large-area, open-field crops, unlike most temperate areas. Augmentative biological control in such large areas present a challenge in maintaining effectiveness, as it relies on the short and rapid action of artificially released biological control agents (Michaud 2018). For field releases, a huge number of agents must be produced and released using sophisticated and automated methods. Nonetheless, augmentative biological control using *Cotesia flavipes* and *Trichogramma* spp. in open fields has worked for sugarcane, maize, and soybean pests in Brazil (Parra 2023). Given South America's position as a global food producer and its rich biodiversity, the private and public sectors must work together to apply biological control in agriculture.

7.1 A Perspective from Argentina

Argentina has around 39.5 million hectares of cultivated land, which represents approximately 14% of the country's total area, mainly with soybean, corn, wheat, barley, sorghum, sugarcane, rice, and sunflower. To a lesser extent it is cultivated with vegetables, legumes, fruits and planted forest (Ritchie et al. 2023). Insecticide application is the technique most used for pest control, mainly in soybeans and horticultural crops (Castagnino et al. 2020). In fact, Argentina has been ranked one of top countries with environmental and human health risks associated with insecticide used in soybeans (Wang et al. 2024). The presence of contaminants from horticultural production, such as pesticides in groundwater and harvested products has also been documented in recent years (Mac Loughlin et al. 2018; Castagnino et al. 2020). For other crops, producers have alternative technologies based on biological principles, such as: 1) transgenic crops producing insecticidal proteins *Bacillus thuringiensis, Bt*-cotton and *Bt*-corn, against some lepidopteran and coleopteran pests (Blanco et al. 2016); 2) sterile insect technique (SIT) for the control of the tephritid fruit flies; 3) mating disruption and mass pheromone trapping for the vine moth, and the pear and apple moth (https://www.iscamen.com.ar/); 4) biological control using microorganisms (Bt, virus, entomopathogens) for several pests in different systems (Starobinsky et al. 2021).

Biological control by entomophagous insects in Argentina has been used since the beginning of the 20th century to the present, but classical biological control was the predominant strategy. From 1908 to 2021, 71 parasitoids and 10 predators were introduced (Greco et al. 2020). Augmentative and classical biological control strategies are not yet widely developed in Argentina. Currently, three development levels of augmentative biological control can be distinguished: 1) commercial, 2) non-commercial and, 3) experimental use of biological control agents. In the first case, there is only one biofactory (http://www.brometan.com.ar; retrieved April 2024) which sells three species of entomophagous produced by Biobest Argentina (Table 8S), which are released in an area of approximately 65 ha. The non-commercial use of biological control agents refers to mass rearing implemented by public institutions that produce biological control agents to be released within the framework of national programs or constitute developed rearing protocols ("know-how") to be transferred to the private sector. On the other hand, experimental releases of several biological control agents have been conducted since 2003 in different agricultural systems mainly by INTA (National Institute for Agricultural Technology), National Universities, and Brometán S.R.L. (Greco et al. 2020).

The development of augmentative biological control in Argentina is still lagging behind because of: (i) a lack of biofactories that produce entomophagous, (ii) scarce knowledge of local biodiversity with potential as biological control agents to avoid the risks associated with the importation of exotic entomophaogous, (iii) discontinuation of research projects that focus on biological pest control, (iv) a lack of strict regulations on the use of synthetic pesticides, (v) low consumer demand for pesticides-free food, and (vi) a lack of public policies that accompany producers in the transition towards organic production. Associated with all this, there are some deficiencies in relevant legislation. For example, the lack of registration for entomophagous and the bureaucracy in each province concerning their release are important issues. For augmentative biological control to make significant progress in Argentina, both the public and private sectors should commit to investing to make this a reality in the near future.

7.2 A perspective from Brazil

Agriculture has underpinned Brazilian economy for a long time (Hopewell 2016). For years, Brazil has been the world's 3rd or 4th largest agricultural producer, earning approximately

$570 billion (ExportsNews 2024). Brazil benefits from favorable climate and soil conditions, enabling the cultivation of a diverse range of crops, fruits, and planted forests. As a result, Brazil is the world's leading producer of soybeans, coffee, citrus, sugarcane and beef, and it ranks as second in the ethanol, and several other commodities. Brazilian agriculture primarily takes place in open fields, where the favorable climate and advanced technologies designed for tropical agriculture enable two to three cropping cycles per year. Nonetheless, Brazil's conventional agriculture boom has increased pest problems and pesticides overuse. In light of such challenges, Brazil has developed crop-specific solutions to overcome such difficulties. Over the past decade, Brazilian scientists have developed effective strategies and technologies for augmentative biological control in large open fields.

The use of biological control in Brazil dates back to the early 1900s, initially focusing solely on the importation of biological control agents (van Lenteren & Bueno 2003; Parra 2014). The first two biological control agents introduced in Brazil were *E. berlesei* in 1921 to control *P. pentagona*, and *Prorops nasuta* (Waterston) in 1929 to control *Hypothenemus hampei* (Ferrari) (Benassi 1996; Parra 2014), both of which were not effective.

Augmentative biological control began to be more actively explored after the establishment of entomology graduate programs at universities in the 1960s and the founding of the Brazilian Entomological Society in 1972. The rearing and release of *C. flavipes* and *Trichogramma* being among the earliest and most notable examples of augmentative biological control in the 1970s and 1980s (Parra 2014, 2023). At present, an estimated 4 million hectares in Brazil are treated with Cotesia and Trichogramma, particularly in sugarcane crops. The use of augmentative biological control in Brazil continues to grow due to several factors: (i) improved regulations and the operation of the Costa Lima quarantine facility, established in 1991 under Embrapa's administration, (ii) specific legislation for faster registration of biological control agents, (iii) increased government and industry research investments, (iv) alignment with the global trend toward sustainable agriculture, (v) support for biological control startups at land-grant universities, (vi) the emergence of new biological control enterprises in the country, and (vii) the expansion of organic agriculture (Togni et al. 2019). Moreover, the invasion by quarantine pests, insecticide resistance, and a shortage of effective insecticides have prompted Brazilian growers to utilize more augmentative biological control. For example, the invasion by *H. armigera* in 2013 (Czepak et al. 2013) was more rapidly and effectively tackled through the use of Baculoviridae-based insecticides and release of *T. pretiosum* (Parra & Coelho-Junior 2019). Lastly, drone technology has also substantially enhanced biological control agent release into large open-field crops, encouraging large farmers to employ more augmentative biological control.

There is a current projection for the Brazilian biological control market to reach revenue of US$80.50 million in 2029 (Mordor-Intelligence 2023). The Brazilian biological control market currently has 159 supplier insectaries offering 17 insect parasitoids and 5 predator species (Table 8S). Additional parasitoid and predator species will be registered and marketed soon (Table 8S). Predator and parasitoid products make about 15% of the biological control agents registered in this market. Despite the great potential for predators and parasitoids, Brazilian growers show more interest in the use of entomopathogen-based insecticides. The extended shelf life and similar application methods to synthetic insecticides may explain this preference. Thus, entomopathogen-based insecticides make up 66% of Brazil's biological control business (Vivan & Querino 2020).

To further advance augmentative biological control in Brazil, researchers, industry, and growers must come together to address several issues, including: (i) the agglomeration of commercial suppliers in southeastern Brazil, which limits accessibility and increases costs for other regions, (ii) technical support for on-farm production of biological control agents to prevent failures and misconceptions about their effectiveness, (iii) improvement of rearing and quality monitoring of biological control agents, (iv) field-release procedures and efficacy assessment, (v) more research to prospect native biological control agents, (vi) implementing conservation measures to support both mass-reared and resident biological control agents, (vii) improving quality control for mass-reared biological control agents, and (viii) enhancing the transfer of technology to industry and growers.

Despite all these challenges, Brazil is making progress in biological control. Such progress and momentum should be taken as a foothold to further promote the science and implementation of biological control in tropical agriculture.

7.3 A perspective from Chile

Chile is flanked by two mountain ranges: the Andes on the east and the coastal mountains on the west, with a north-south longitude of 4,300 km. These mountains form geographical units with distinct flora, fauna, and ecosystems based on latitude and altitude (Esquerre et al. 2019) determining the regime of the rivers, climate, and human activities like agriculture. Agroecosystems are in rain-fed coastal ranges, Andean slopes, and watersheds of the Central Valley (Altieri & Rojas 1999). The Andes act as a biological barrier to pests and provide rich local biodiversity, with many native and endemic species. This region is considered one of the 36 global biodiversity hotspots (The Confederation of European Forest Owners – CEPF 2023). Consequently, agroecosystems host a wide variety of beneficial insects that could help in pest control. However, many biological control agents in the country are exotic species that were imported in classical biological control programs or have been accidentally introduced. About 73% of parasitoid species (Fernandez et al. 2023), and 13% of ladybird beetles are exotic (Gonzalez 2019).

Chile first used biological control in 1903 by introducing a predator for the olive black scale *Saissetia oleae* (Oliver) (Barra-Bucarei et al. 2023). Many classical biological control agents were brought into Chilean fields without restriction prior to the 1960s, followed by a period when all imported biological control agents were quarantined (Rojas 2005). The Department of Agriculture formalized classical biological control in 1915. The first successful biological control program in Chile was in 1921, with the introduction of the parasitoid *Aphelinus mali* (Haldeman) to control the woolly apple aphid, *Eriosoma lanigerum* (Hausmann), in apple orchards. Furthermore, Chile is known for the success of aphid biological control programs in cereals using a complex of Aphidiinae species between 1979 and 1992 (Starý 1993). These programs had effective control over pest aphid populations and reduced insecticide application in cereal crops. Until 2005, over 80 beneficial insect species had been imported to Chile for pest control, and 53% of them had successfully established (Lavandero et al. 2006). To support the establishment of introduced natural enemies and promote those of the agroecosystem, cover crops (Alvarez-Baca et al 2022), strips with native and exotic plants (Peñalver-Cruz et al. 2019) and insecticide programs with low natural enemy mortality have been implemented.

Changes in national and international regulations for the use of synthetic pesticides have increased the demand for biological control agents (Coria & Elgueta 2022). This situation has encouraged companies, research centers, and universities in Chile to conduct research, technology transfer, and the commercialization of biological control agents (Barra-Bucarei et al. 2023). However, the vast quantity of documents required, and high costs are significant barriers to registering biological control agents in Chile (Barra-Bucarei et al. 2023). Currently, there are about 10 national companies selling biological control agents in Chile, with some started as spin-offs from universities (e.g., https://bionativa.cl/). The market for augmentative biological control in Chile is estimated at $25 million per year (Dr. Donoso, Bioinusumos Nativa, personal communication), with over 7 million hectares under classical biological control, and 62,000 hectares under augmentative biological control (Barra-Bucarei et al. 2023). In addition, the concern of the negative effects of exotic species on native biodiversity in Chile has promoted methodologies and protocols to mitigate them (Fernandez et al. 2023). These protocols assess ecological aspects related to the ability of the new species to establish, disperse, and their host range. Focused on indigenous species, the National Institute of Agricultural Research (INIA) has started studying native parasitoids of *D. suzukii* in Chile to establish a biological control program without introducing additional agents. Devotto-Moreno et al. (2022) have already recorded the parastoids *Pachycrepoideus vindemmiae* (Rondani), *Leptopilina boulardi* Barbotin, and *Ganaspis* sp. They are searching for more parasitoid species in a national survey.

Biological control is widely employed in Chile, but farmers need better technology to apply it. Therefore, to encourage the use of biological control, the following are needed: 1) subsidies for farmers to acquire biological control agents; 2) promoting research by national institutions on trophic interactions that affect biological control; 3) training farmers to identify beneficial insects; and 4) practical advice on the use of biological control agents in the field. Recent programs for small farmers, TAS (http://www.indap.gob.cl/plataforma-de-servicios/transicion-la-agricultura-sostenible-tas) provide knowledge-based solutions and subsidies for sustainable practices, including classical and augmentative biological controls.

7.4 A perspective from Colombia

Colombia's diverse geography enables the production of an exceptionally wide variety of tropical and subtropical crops. Despite such diversity, this review perspective will focus on some of the most economically important crops, where technological efforts have been made to promote biological control.

Coffee is Colombia's most important export product after petroleum, and it has been the backbone of the Colombian economy. The coffee berry borer (CBB) *H. hampei* constitutes the main pest of the crop in the country. Multiple efforts have been made to establish an IPM program focused on cultural practices and biological control (Bustillo 2018). Applications of *Beauveria bassiana* have been reported as efficacious against the CBB, but climatic conditions and strain virulence produce variable results (Tobar et al. 1999). Several parasitoid species have been reported for use against CBB, including three African species, *Phymastichus coffea* (La Salle), *P. nasuta*, and *Cephalonomia stephanoderis* Betrem, which were introduced through importation (Bustillo 2018). Although these species have established in the field, they exhibit low levels of parasitism.

The harvest of all berries and cultural practices such as sanitation are also important CBB IPM components (Benavides et al. 2002). These practices, however, may remove mature berries with parasitoid larvae, which could hinder natural biological control (Cure et al. 2020). In general, the classical biological program is considered successful as it established a new set of biological control agents that now inhabit the Colombian coffee agroecosystems (Bustillo 2018).

Colombia is the world's second-largest producer of roses, with most cut-flower production taking place in greenhouses located in the high plains surrounding Bogotá, Rionegro, and Medellín. The flower western thrips *F. occidentalis* and the leafminers *Liriomyza* spp. are considered important pests (Corredor 1999). Most flower cut production is exported; hence customs in different ports of entry have limited insect and mite tolerance. Therefore, the flower-cut industry faces constraints such as international restrictions on the use of pesticides, the high price of new molecules, the ban of some old active ingredients, and the need to work towards more sustainable management. The latter has opened the door to using more biopesticides and biorationals based on *B. bassiana, Metarhrizium anisopliae*, entomopathogenic nematodes, and botanical extracts. A limited list of predatory insects is also available, including *C. carnea* and *O. insidiosus*. Nonetheless, the adoption of it among growers is considered low. Environmental regulations in Colombia impose strict limitations on the use of introduced natural enemies, and the procedures for registering biopesticides have yet to be fully aligned with international standards (Santos et al. 2018). As a result, the registration process remains unnecessarily lengthy and discouraging. This highlights the need for greater collaboration among academia, the cut-flower industry, and private commercial biofactories to foster the development and production of locally sourced natural enemies.

Colombia is Latin America's largest palm oil producer, with nearly 450,000 hectares grown in 2020. In early crop ages, the abundance of other plant resources could be the reason for a higher abundance of biological control agents and a reduction in pest insects. However, as the crop progresses in age, plant diversity is reduced, and the number of insect pests increases (Calvache 1995; Bustillo-Pardey 2014). This has provided an opportunity to use more conservation biological control,leveraging the diverse range of beneficial insects in the palm oil system. In this context, the Colombian oil palm industry has developed an agroecological and biodiversity conservation approach for this agroecosystem. Plants with extra-floral nectaries are grown in areas to increase biodiversity and beneficial insects. Aldana et al. (1997) reported parasitoid species associated with alternative vegetation in the palm oil agroecosystem, which parasitize economically important pests.

After coffee, sugarcane is considered the second-most important agroindustry in Colombia where approximately 500,000 hectares of sugarcane are grown to produce non-refined sugar, sucrose, and ethanol. The sugarcane stem borers *Diatraea* spp. are the most important pests of sugarcane in Colombia, which are managed by continuous mass-production and releases of the egg parasitoid *Trichogramma exiguum* Pinto and Platner, and larval parasitoids such as *Lydella minense* (Towndsend) and *Cotesia flavipes* Cameron (Vargas et al. 2018). In some locations, however, the most important larval parasitoid is *Genea jaynesi* (Aldrich) (Sarmiento-Naizaque et al. 2021; Vargas et al. 2018). However, the mass rearing efforts of *G. jaynesi* have failed, prompting a shift toward conservation efforts aimed at enhancing its function. As a result, there is an extensive focus within the entire sugarcane industry on promoting the study and conservation of natural habitats surrounding sugarcane fields.

Several challenges persist in establishing more effective biological control programs in Colombia, including technical hurdles related to the study of beneficial organisms and the promotion of their adoption among growers. The absence of a formal extension service through the government or public universities hinders the adoption of biological control, leaving farmers dependent on the efforts of a few dedicated professors who voluntarily engage in outreach, and on a few private companies that promote their own pest management solutions. Moreover, government regulations on beneficial organisms continue to discourage investment in biological control, particularly regarding the registration of commercial parasitoids. A recent survey found that only three out of 39 consulted insectaries reported registered products (Lohr 2018). In response, a group of private companies has formed the Association of Biological Control Producers (Asobiocol 2024) to promote technology development, train personnel, disseminate regulatory updates, and strengthen ties with various crop industries.

8 Final remarks

1. Augmentative biological control focuses on supplying growers with mass-reared biological control agents to manage pest species. This approach can often achieve pest control comparable to conventional methods. Consequently, augmentative biological control is highly appealing to the private sector, which benefits financially from the substantial demand for these biological solutions.
2. Although the number of biological control agents being investigated and marketed is growing, it still falls significantly short of the range needed for effective use alone or as part of an IPM strategy. Biocontrol gents based on entomopathogens are far more used than predators and parasitoids.
3. The area of open fields treated with augmentative biological control has expanded in the tropics thanks to new biological control agents-release technologies (e.g. drones). However, further expansion is constrained by the limited number of biological control agents commercially available and by limited knowledge regarding how field aspects can interact with released biological control agents.
4. Efforts to prospect for native biological control agents for augmentative biological control are advancing. This initiative is often driven by the growing interest from the private sector.
5. Discovering biological control agents and integrating them into new augmentative biological control programs remains a challenging task. However, there are efforts to develop a comprehensive risk assessment approach that emphasizes the specificity. This approach takes into account their biology and ecology, tailoring them to the target pest and local climate, where they are released.
6. There are concerns about whether existing and new augmentative biological control programs can adapt to

both local and global climate changes while meeting growers' needs for more cost-effective and profitable food production methods.

7. Advancements in managing the mass rearing process, releasing biological control agents in large open fields, and evaluating the results have all fueled increasing interest in augmentative biological control. Additionally, implementing conservation alongside augmentative biological control holds the potential to enhance the effectiveness of mass-reared biological control agents after being released in the field. Lastly, biological control has also the potential to engender beneficial indirect effects which ought to be assessed.
8. IPM technologies, such as Bt- and conventional-resistant plants, more selective synthetic, biological, and botanical insecticides (with more specificity), and other sustainable farming practices, are vital to the augmentative biological control program's success.
9. There is a significant expectation for an increased availability of biological control agents due to the public and private sector's interest in minimizing the impact of food production on the environment and human health.

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