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COMMISSION ON GENETIC RESOURCES FOR FOOD AND AGRICULTURE

# SUSTAINABLE USE AND CONSERVATION OF MICROBIAL AND INVERTEBRATE BIOLOGICAL CONTROL AGENTS AND MICROBIAL BIOSTIMULANTS

BACKGROUND STUDY PAPER NO. 71

# SUSTAINABLE USE AND CONSERVATION OF MICROBIAL AND INVERTEBRATE BIOLOGICAL CONTROL AGENTS AND MICROBIAL BIOSTIMULANTS


**Rosemarije Buitenhuis**, *Vineland Research and Innovation Centre, Canada*

**Matthew J.W. Cock**, *CABI, United Kingdom of Great Britain and Northern Ireland*

**Yelitza C. Colmenarez**, *CABI Latin America, Brazil*

**Patrick De Clercq**, *Department of Plants and Crops, Ghent University, Belgium*

**Steven Edgington**, *CABI, United Kingdom of Great Britain and Northern Ireland*

**Patricia Gadaleta**, *Dirección de Producciones Sostenibles, Secretaría de Agricultura, Ganadería y Pesca, Ministerio de Agricultura, Ganadería y Pesca, Argentina*

**Roma Gwynn**, *Biorationale, United Kingdom of Great Britain and Northern Ireland*

**George Heimpel**, *Department of Entomology, University of Minnesota, United States of America*

**Martin Hill**, *IOBC, Centre for Biological Control, Rhodes University, South Africa*

**Hariet L. Hinz**, *CABI, Switzerland*

**Mark S. Hoddle**, *Department of Entomology, University of California Riverside, United States of America*

**Thomas Jäkel**, *International Rice Research Institute, Rice Department, Thailand*

**Johannette N. Klapwijk**, *Koppert Biological Systems, Netherlands*

**Kelley Leung**, *Groningen Institute for Evolutionary Life Sciences, University of Groningen, Netherlands*

**Fernando Mc Kay**, *Fundación para el Estudio de Especies Invasivas, Argentina*

**Gerben J. Messelink**, *Wageningen University & Research, Netherlands*

**Luciana Silvestri**, *Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina*

**David Smith**, *CABI, United Kingdom of Great Britain and Northern Ireland*

**Alejandro Sosa**, *Fundación para el Estudio de Especies Invasivas, Argentina; Consejo Nacional de Investigaciones Científicas y Técnicas, CABA, Argentina*

**Felix L. Wäckers**, *Biobest, Belgium; Lancaster University, United Kingdom of Great Britain and Northern Ireland*

**Guillermo Cabrera Walsh**, *Fundación para el Estudio de Especies Invasivas, Argentina*

**Kris A.G. Wyckhuys**, *Chrysalis Consulting, Viet Nam*

**Tania Zaviezo**, *Facultad de Agronomia e Ingeniera Forestal, Pontificia Universidad Católica de Chile, Chile*



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# Abbreviations and acroynms

| | |
|---|---|
| ABS | access and benefit sharing |
| ABRCN | Asian Biological Resource Centre Network |
| ACM | Asian Consortium for the Conservation and Sustainable Use of Microbial Resources |
| AMF | arbuscular mycorrhizal fungi |
| ASEAN | Association of Southeast Asian Nations |
| BCA | biological control organism |
| BPH | brown planthopper |
| BRC | Biological Resource Centre |
| Bt | *Bacillus thuringiensis* |
| CABI | Centre for Agriculture and Bioscience International |
| CABUA | Comité Asesor en Bioinsumos de Uso Agropecuario (Argentina) |
| CBD | Convention on Biological Diversity |
| Commission | Commission on Genetic Resources for Food and Agriculture |
| CSA | climate-smart agriculture |
| Defra | Department for Environment, Food and Rural Affairs (United Kingdom of Great Britain and Northern Ireland) |
| DSI | digital sequence information |
| EFSA | European Food Safety Authority |
| EPPO | European and Mediterranean Plant Protection Organization |
| EU | European Union |
| EUR | euro |
| FAO | Food and Agriculture Organization of the United Nations |
| FFS | farmer field school |
| GCM | Global Catalogue of Microorganisms |
| GHG | greenhouse gas |

| | |
|---|---|
| GRFA | genetic resources for food and agriculture |
| IAEA | International Atomic Energy Agency |
| IAS | invasive alien species |
| IBMA | International Biocontrol Manufacturers Association |
| IOBC | International Organization for Biological Control |
| IOBC-GCABS | International Organization for Biological Control – Global Commission on Access and Benefit Sharing |
| IPBES | Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services |
| IPPC | International Plant Protection Convention |
| IPM | integrated pest management |
| IRAC | Insecticide Resistance Action Committee |
| IRM | insecticide resistance management |
| ISPM | International Standards for Phytosanitary Measures |
| IUCN | International Union for Conservation of Nature |
| mBRC | microbial domain Biological Resource Centre |
| MIRRI | Microbial Resources Research Infrastructure |
| MoA | mode of action |
| MOSAICC | Micro-Organisms Sustainable use and Access regulation International Code of Conduct |
| MRL | maximum residue level |
| NAPPO | North American Plant Protection Organization |
| NBSAP | National Biodiversity Strategy and Action Plan |
| OECD | Organisation for Economic Co-operation and Development |
| PGPR | plant growth-promoting rhizobacteria |
| RSPM | Regional Standard for Phytosanitary Measures |
| POP | persistent organic pollutant |
| SDG | Sustainable Development Goal |
| SPS | sanitary and phytosanitary |

| | |
|---|---|
| STI | science, technology and innovation |
| USD | United States dollar |
| WDCM | World Data Centre for Microorganisms |
| WFCC | World Federation for Culture Collections |
| WHO | World Health Organization |
| WTO | World Trade Organization |
| 3G3T | Three Reductions, Three Gains (policy) (Viet Nam) |

# Executive summary

## Introduction

**Interest in the use of microbial and invertebrate biological control agents (BCAs) in food and agriculture is increasing.**[1] Growing concerns about the impact of pesticide use on biodiversity and human health – and increasing demand for products from biodiversity-friendly production systems, including organic systems – have led to growing interest in alternative methods of pest control, including particularly the use of microbial and invertebrate BCAs.

**Microbial and invertebrate BCAs comprise microorganisms and invertebrates that induce an action against target organisms that cause harm to humans or their resources.** Four categories of biological control can be distinguished:

- natural biological control: the suppression of populations of harmful species by living organisms (or viruses) that occurs without deliberate intervention by humans for this purpose;
- a diverse set of practices that aim to preserve and enhance the activity of natural enemies to improve existing levels of pest control and thereby reduce the negative effects of harmful species;
- classical biological control: the deliberate importation, release and establishment of natural enemies in areas where they did not previously exist to reduce non-native invasive pest populations to less-damaging levels; and
- augmentative biological control: an approach in which natural enemies of pests or antagonists of pathogens are mass-reared under controlled conditions and released with the aim of temporarily suppressing arthropod pests or diseases.

[1] This study was prepared in order to support the Commission on Genetic Resources for Food and Agriculture's Work Plan for the Sustainable Use and Conservation of Micro-organism and Invertebrate Genetic Resources for Food and Agriculture. A draft was made available to the Eighteenth Regular Session of the Commission (CGRFA-18/21/11.2). The final version takes into account comments provided at the Commission session.

**Microbial and invertebrate BCAs benefit all the sectors of food and agriculture.** Microbial and invertebrate BCAs provide natural biological control across a wide range of terrestrial and aquatic environments used for crop and livestock production, forestry, fisheries and aquaculture or that are not used for production but provide ecosystem services of importance to the food and agriculture sector (and often human well-being more generally). In many cases, BCAs are also deliberately used to control species regarded as undesirable in the given location (in some cases because of their environmental impacts). Deliberate use specifically against the pests, diseases and weeds directly impacting production is commonest in the crop (including forage crop) and forest sectors, but there are some applications in livestock production.

**Microbial biostimulants are attracting increasing attention as sustainable alternatives to synthetic inputs in crop production.** Biostimulants have been defined as "fertilising product[s] the function of which is to stimulate plant nutrition processes independently of the product's nutrient content with the sole aim of improving one or more of the following characteristics of the plant or the plant rhizosphere: (a) nutrient use efficiency, (b) tolerance to abiotic stress, (c) quality traits, or (d) availability of confined nutrients in the soil or rhizosphere" (du Jardin, 2015; European Union, 2019) They may strengthen strengthen plants' natural defences against pests and diseases. The main groups of microbial biostimulants are plant growth-promoting rhizobacteria and arbuscular mycorrhizal fungi.[2]

## State of adoption

**Natural biological control plays an important role in production systems throughout the world.** The significance of the services provided by non-managed microorganisms and invertebrates is illustrated by the pest outbreaks that occur when natural enemies are eliminated through the inappropriate use of pesticides. Natural biological control is, by definition, not "adopted" by humans as it occurs independently of human action. However, information on the levels of natural biological control

[2] At the Commission's request, the study covers both microbial and invertebrate BCAs and microbial biostimulants.

impacting pest populations can be used to adjust recommendations on threshold pest densities above which pesticides need to be applied in order to avoid economic damage.

**There is evidence that the adoption of conservation biological control is increasing, although rates of uptake vary from region to region**. Research-driven implementation has been documented in a variety of production systems, mostly in Europe and North America, and there have been examples of successful implementation in many parts of the world.

**Knowledge gaps are an important barrier to the further adoption of conservation biological control**. Constraints include a lack of detailed knowledge of the targeted agroecosystems. Guidance on the implementation of conservation biological control is improving, but there is a need to strengthen research on the ecology of BCAs and the impacts of specific management practices (e.g. the use of flowering vegetation).

**Adoption of classical biological control is uneven across the countries and regions of the world**. Australia, Canada, New Zealand, South Africa, the United States of America and various European countries have well-developed classical biological control programmes for arthropod pests and weeds. The importance and utility of biological control for the management of invasive pests in Africa has been recognized, and there have been some very successful programmes targeting insect pests and weeds in the region. There have also been some successful programmes in the Near East and across much of Asia. Efforts have been increasing in China. Use of classical biocontrol against insect pests is increasing steadily in Latin America, although use against weeds is still very limited. In these latter areas, there are many opportunities to develop programmes that would be likely to be highly successful if they were well designed and funded and appropriate targets selected. In all regions, classical biological control programmes are usually government-led "public good" initiatives.

**Constraints to the further adoption of classical biological control include regulatory and resourcing barriers**. Constraints include declining investment – specifically a lack of financial support for multi-year programmes and projects – a declining number of scientists specializing in classical biological control, aging and oversubscribed infrastructure (e.g. quarantine facilities), increasing regulatory hesitancy over perceived environmental risks, and increasing restrictions on access to new BCAs caused by implementation of access and benefit-sharing (ABS) measures.

**Adoption of augmentative biological control has increased markedly over recent years**. This form of biological control is largely a commercial activity. Over the last decade, market growth for biological control products has outperformed that of chemical pesticides, and augmentative biological control has become the main crop protection strategy for a number of protected crops.[3] The worldwide market for biological control products (including semiochemicals and natural products in addition to BCAs *per se*) was USD 4.1 billion in 2019. Adoption in Europe and North America is primarily in protected cropping of vegetables, fruits and ornamental species. However, use on open-field crops is growing, with successful examples in vineyards, horticulture and arable crops (maize). In developing countries, this form of biological control has been successfully adopted in sugar-cane and maize production. There are some examples of augmentative biological control solutions developed for use by smallholders. There are also several cases where augmentative biological control has been used against weeds that have impacts on the environment outside food and agricultural production systems.

**Constraints to the further adoption of augmentative biological control include overly restrictive regulatory measures and the lack of integration with other sustainable agricultural practices**. Factors contributing to regulatory constraints include a lack of knowledge on the part of regulatory agencies overseeing the importation, distribution and use of commercially available BCAs. There is also a need to ensure that augmentative biological control is integrated with other sustainable practices such as the use of disease-resistant crop varieties, crop rotation, good soil management and maintenance of landscape features that provide habitat resources for BCAs.

**The market for biostimulants is steadily growing**. Drivers of this market growth include increasing consumer preferences for organic and other sustainably produced foods, and changes in laws and regulations related to the use of synthetic fertilizers and pesticides. The global biostimulant market is estimated to have been worth USD 2.6 billion in 2019 and is projected to reach USD 4.9 billion by 2025.

## Status, trends and threats

**Microbial and invertebrate BCAs face a variety of threats**. A lack of data makes it difficult to make firm

[3] Crops protected by greenhouses, polytunnels or other artificial structures.

statements about the status and trends of microbial and invertebrate BCAs. However, for insects in general (a group that includes many BCAs) there are reports of population declines in many ecosystems.

**Microbial and invertebrate BCAs are being harmed by unsustainable practices in the food and agriculture sector.** The status of the species that supply biological control services depends on multiple factors, but unsustainable management practices in agriculture are a substantial threat. The intensification of crop production, with larger fields, reduced field margins, elimination of non-crop vegetation, intensive soil preparation and use of insecticides has negative effects on BCA habitats and BCA diversity and abundance. Where remedial measures (e.g. as the establishment of refuge areas of habitat) are not being implemented, it is possible that many BCAs are being eliminated from large areas and that species, and especially locally adapted strains, are at risk of localized or global extinction. Climate change (to which the agriculture sector is a major contributor) is an exacerbating factor.

**It is likely that negative drivers such as land-use change and climate change are leading to local and potentially global extinctions of wild BCA species.** The species used in classical and augmentative biological control are sometimes rare in their areas of origin and therefore vulnerable to the effects of negative drivers of this kind. Species that could play important roles in these types of biological control but whose potential use in such programmes has never been considered may be at risk of loss.

## The state of management

**Microbial and invertebrate BCAs are subject to a range of management interventions.** These interventions include the various activities involved in the use and conservation of BCAs, i.e. in implementing conservation, classical and augmentative biological control (including genetic improvement, mass-rearing and related activities) and in minimizing the loss of the BCA diversity needed to supply pest-control services now and in the future.

### *Conservation*

***In situ* conservation efforts targeting microbial and invertebrate BCAs are limited.** Species used in classical or augmentative biological control are maintained through use, both via mass rearing in captivity and via various measures taken to ensure that released populations flourish in the areas targeted. However, wild source populations that harbour high levels of genetic diversity may be threatened. It can be assumed that these source populations benefit from *in situ* conservation measures targeting biodiversity in general (e.g. the establishment of protected areas), but there is little indication that protecting BCAs is a specific objective in such efforts. It can also be assumed that conservation biological control practices help maintain the size and diversity of microbial and invertebrate BCA populations in and around the production systems where they are applied. However, broader conservation measures may be needed to address threats to the species concerned.

**Additional research attention needs to be given to *in situ* conservation strategies for microbial and invertebrate BCAs.** In the case of microbial BCAs in particular, lack of attention to *in situ* conservation is part a consequence of knowledge gaps that make it difficult to plan conservation activities and monitor their impacts. An estimated 99 percent of all microbial species remain undescribed, and there are likely to be many unknown microbial species that may have high potential efficacy in biological control programmes.

***Ex situ* conservation measures for microbial BCAs need to be better coordinated and documented.** Many microbial BCAs are maintained *ex situ* for research or for applied use in the field. In some cases, these organisms are put into secure long-term storage. However, strains are often lost, for example because of inappropriate storage methods or because research programmes end and colonies are destroyed. Strains that are used commercially are maintained while these activities continue. However, there is no overall coordination, and comprehensive information on the range of organisms maintained and on their genetic diversity is not available. Efforts are needed to obtain a better overview of what microorganisms are included in existing collections and the potential these have for use in biological control. Attempts have been made to address such information gaps at an international scale, for instance through the development of the Centre for Agriculture and Bioscience International's (CABI's) Bioprotection Portal,[4] which provides information on registered BCA products (microbial and invertebrate BCAs, natural substances and semiochemicals) across 15 countries.

**Efforts are needed to improve the status of public-service *ex situ* collections of microbial BCAs, particularly in the developing regions of the world.** The World Data Centre for Microorganisms

[4] https://bioprotectionportal.com/

(WDCM) documents more than 800 collections globally.[5] However, these collections are largely concentrated in developed countries. For example, although Africa has vast microbial diversity, its 18 collections registered with the WDCM hold fewer than 18 000 strains, whereas Europe, by comparison, has a total of more than 1.1 million strains, held in 256 collections.

***Ex situ* conservation of invertebrate BCAs remains very limited because of the difficulties involved in maintaining invertebrates in *ex situ* conditions**. Promoting the *ex situ* conservation of invertebrate BCAs would be desirable, particularly in the case of species that have application in classical biological control and for which *in situ* conservation is limited or not possible. However, *ex situ* conservation of invertebrates remains technically challenging. There is a need to develop technologies and best practices that would ensure the genetic integrity of invertebrates maintained in living cultures. Cooperation among countries to coordinate conservation activities for invertebrate BCAs would also be needed.

### *Genetic improvement*

**While mass rearing of invertebrate and microbial BCAs is widespread, genetic improvement remains largely confined to research**. The application of genetic improvement methods to BCAs has been limited because of the amount of time involved, the high levels of knowledge required and the availability of the option of importing new strains – although the situation may be changing. Artificial selection of invertebrate BCAs has proved successful at the research level. Studies have tended to focus on insecticide resistance, but selection has been successfully implemented for traits such as developmental diapause (relevant for storage), fecundity and host adaptation. Evolutionary trade-offs have been identified as a significant problem for artificial selection. It has therefore been suggested that there is a need for selection regimes that are closer to natural conditions.

**Options such as genomic selection and combining breeding populations (to increase genetic diversity and potentially deliver hybrid vigour) are attracting some interest**. Genetic modification of BCAs has been repeatedly suggested, but it is considered unlikely to become common given its incompatibility with the "environmentally friendly" reputation of biological control (e.g. in the context of organic production) and because of legal restrictions. The need for long-term investment is also a constraint. Manipulating the microbiome of BCAs or plants is another option that has attracted some interest.

**Constraints to progress in the genetic improvement of invertebrate and microbial BCAs include regulatory restrictions and knowledge gaps**. The latter include a lack of available information on the genetic diversity of populations potentially targeted for genetic improvement and on the traits relevant for field efficacy.

**Genetic improvement is not currently an option in the case of arbuscular mycorrhizal fungi used as biostimulants**. The specific characteristics of fungal genetic systems mean that use of classical breeding and other methods of genetic improvement to obtain populations with stable, desirable traits is not possible at present.

### The state of policies and legal instruments

**The management of invertebrate and microbial BCAs is affected by a variety of policy and legal instruments at global, regional and national levels**. These instruments can operate both as enablers and as disablers of effective action. Key international legal frameworks include the International Plant Protection Convention (IPPC) and the Convention on Biological Diversity (CBD). The IPPC's Commission on Phytosanitary Measures develops and adopts International Standards for Phytosanitary Measures (ISPMs), which are recognized by the World Trade Organization as the basis for trade-related phytosanitary measures. The CBD and its Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization are intended to ensure the conservation and sustainable use of all biodiversity, including BCAs, and the equitable sharing of benefits arising from their use. Many countries have laws and policies in the fields of plant and environmental protection that address aspects of the use of BCAs, such as import and registration procedures.

**Biological control strategies are relevant to a wide range of policy goals, including many of the Sustainable Development Goals (SDGs), but they are often not mainstreamed into relevant policy frameworks**. Potentially relevant policy areas include science, technology and innovation, education for stakeholders in the agrifood system, food safety, climate change, occupational health and safety, trade, biodiversity conservation and ecosystem restoration, and post-COVID 19 recovery.

**Numerous policy levers can potentially be used to promote more widespread adoption of biological**

[5] http://gcm.wdcm.org/datastandards

**control and to drive innovation in this field**. Options include both soft policy measures (e.g. certification schemes and food-safety labelling) and hard policy measures (e.g. conditional financial assistance, more stringent maximum residue limits, pesticide taxes and substance bans). Crop insurance schemes can potentially help reduce the tendency for producers to opt for strategies based on heavy use of pesticides.

**Important enabling factors for biological control include intergovernmental and other international collaboration, adherence to international regulations, well-funded research facilities and efficient procedures for their use, and effective training of biological control practitioners**. Excessively stringent risk-assessment requirements have been a major roadblock to the introduction of BCAs in many parts of the world. Efficient procedures for assessing the benefits and risks of biological control relative to alternatives such as pesticide-based approaches are needed. In many cases, legal frameworks for registering augmentative biological control products need to be simplified and harmonized.

Obstacles encountered by biological control researchers and practitioners include complicated access procedures and lack of institutional capacity for enabling compliance with ABS rules. Difficulties in meeting national ABS requirements have led to problems including long delays in registering BCAs, loss of funding and cancellation of projects. Another issue is that different countries have different criteria for determining which uses of genetic resources require benefit-sharing under mutually agreed terms. Free multilateral exchange across a global network of professionals has been a key element of biological control practice and needs to be given due attention in ABS measures, potentially via simplified procedures or exemptions for exchanges occurring for biological control purposes if they support the public good and/or protect the environment.

**Due attention needs to be given to the sharing of non-monetary benefits associated with the use of invertebrate and microbial BCAs**. Given that classical BCAs are provided as free-of-charge public-good contributions to all countries and that the net profit margins of companies selling BCAs commercially are small, where ABS laws require the negotiation of mutually agreed terms, non-monetary benefits should be among the benefit-sharing options considered. Non-monetary benefits can be provided by closely involving local entities (universities, research institutes, regulatory authorities, indigenous peoples and local communities) in the provider countries in the scientific aspects of the biological control projects, including participation in field exploration, exchange visits, training of students and scientists, joint authorship of scientific publications and joint submission of research proposals.

**The emergence and expansion of "digital sequence information" (DSI) may have implications for the use of microbial and invertebrate BCAs**. Taxonomic identification of BCAs and target pests by means of morphological or molecular analyses is a crucial step in biological control projects. The rise of genetic sequence data in the public domain has further complicated the already difficult issue of traceability for negotiations over benefit-sharing.

**Some regulatory measures have been put in place for biostimulants**. The revised European Union (EU) Fertilising Products Regulation (2019/1009), which includes regulation of plant biostimulants, is expected to be applied in EU Member States in 2022. Several countries in Europe, as well as Brazil, Canada, India, South Africa and the United States of America, have regulations related to biostimulants.

## Options for action

**Action on the part of a range of stakeholders, including national governments and intergovernmental bodies, is urgently needed to address the numerous knowledge gaps, resource limitations and legal, policy and institutional weaknesses that constrain the development of biological control and to tackle the numerous threats facing BCAs**. Key areas in which action is needed at governmental and intergovernmental levels, including potentially by the Commission and its Members, are discussed in the following paragraphs. Box 1 presents ten specific recommendations for action.

### *Conservation*

Efforts to address threats to microbial and invertebrate BCAs, and to a lesser extent microbial biostimulants, and to promote conservation measures for them are urgently needed. Microbial and invertebrate BCAs and microbial biostimulants can be expected to benefit from generic actions that lead to improvements in the conservation of the microorganism and invertebrate biodiversity found in and around production systems. However, some specific priorities can be identified. With regard to *ex situ* conservation of BCAs, there is a need to support efforts to improve coordination among culture collection organizations. Capacity to store whole microorganism communities (microbiomes) is providing new opportunities for *ex situ* conservation, and there is a need to ensure that microbial BCAs and biostimulants are adequately included in initiatives in this field.

**Box 1. Recommendations for the sustainable use and conservation of microbial and invertebrate biological control agents and biostimulants**

*Recommendation 1.* The conservation of natural enemies for biological control in crops and natural habitats should be an explicit objective in international standards on good agricultural practices and stewardship of natural areas, and in national and international policy for integrated pest management.

*Recommendation 2.* National and international measures should be taken to strengthen research, including public-sector research, on the taxonomy and use of biological control agents (BCAs) and to improve collections and other services (e.g. training of PhD-level scientists) and infrastructure (e.g. laboratories and quarantine facilities) that support biological control.

*Recommendation 3.* National and international measures should be taken to educate farmers and conservationists on the benefits of natural enemies and their management and to increase their participation in research and implementation in order to promote successful uptake of biological control.

*Recommendation 4.* National and international measures should be taken to promote community science initiatives that would engage the general public in the study and conservation of natural enemies.

*Recommendation 5.* National and international measures should be taken to improve knowledge of the negative effects of pesticides on natural enemies, and this knowledge should be made openly accessible for farmers.

*Recommendation 6.* The conservation of habitats of natural enemy species for biological control of future non-native pest problems in other countries should be an explicit element of national and international measures to conserve biodiversity in agroecosystems and natural ecosystems. Conservation and sustainable use of natural enemies can be further formalized and applied through conservation biological control practices.

*Recommendation 7.* Government authorities should adopt simplified measures for access to and exchange of BCAs or consider exemption of these activities from the scope of access and benefit-sharing regimes.

*Recommendation 8.* Governments should develop appropriate national regulatory systems for BCAs that encourage and support the development of new agents for classical biological control and methods to enhance augmentative biological control. They should harmonize regulatory requirements and promote knowledge sharing at the international level to facilitate the development of effective biological control programmes.

*Recommendation 9.* In considering future measures for conservation and use of genetic resources for food and agriculture, governments should consider a broad approach to the conservation and sustainable use of biodiversity, including access to knowledge and capacity building: components of such an approach will help improve the management of BCAs.

*Recommendation 10.* Governments should encourage initiatives that educate the public on the benefits of biological control, including its role in protecting the food supply (Sustainable Development Goal [SDG] 2), improving health (SDG 3), and reducing the negative impacts of agriculture on the environment (SDG 12) and the climate (SDG 13).

*Note*: The recommendations presented in this box build on those presented in Waage, J. 2007. *The sustainable management of biodiversity for biological control in food and agriculture: status and needs.* Commission on Genetic Resources for Food and Agriculture. Background Study Paper No. 57. Rome, FAO.

### *Sustainable use*

The uptake of microbial and invertebrate BCAs and microbial biostimulants in food and agriculture needs to be promoted. This is particularly the case in developing countries, where BCAs and biostimulants could have a substantial impact in terms of increasing productivity, reducing environmental degradation and improving safety.

Promoting uptake will require a facilitating framework with respect to, *inter alia*, the state of knowledge, capacity, cooperation, policy and legislation (see below). Despite progress at the research level, genetic improvement of BCAs has had little practical impact to date. Constraints related, inter alia, to ABS issues and to knowledge gaps need to be addressed (see below).

### *Exchange*

Ensuring efficient exchange of microbial and invertebrate BCAs, including internationally, is vital to the development and implementation of biocontrol practices. Activities related to policy-development or awareness-raising in the field of ABS therefore need to take the concerns of the biocontrol sector into account. Practical steps could include the establishment of an interactive site via which importing and exporting countries could establish terms of exchange. The development of a multilateral framework specifically aimed at facilitating access to and use of microbial and invertebrate BCAs and the sharing of benefits arising from their use could be considered.

### *Knowledge gaps*

Improvements to the management of microbial and invertebrate BCAs and microbial biostimulants require knowledge of their characteristics, their roles in the supply of ecosystem services, their risk status and distribution, the threats affecting them, techniques for their use and conservation, and the status and trends of the adoption of practices involving their use. Research on the management of BCAs and biostimulants can potentially be facilitated via capacity development, promoting access to data and information, developing or strengthening policy and legal frameworks, and promoting collaboration among researchers and between researchers and other stakeholders.

### *Capacity development*

The critical lack of human and material resources for the identification and characterization of microbial and invertebrate BCAs and microbial biostimulants, especially those that provide natural or conservation biological control, needs to be addressed. Action is particularly required in tropical and subtropical areas.

### *Policy and legal frameworks*

National policy and legal frameworks for the management of microbial and invertebrate BCAs and microbial biostimulants often need to be strengthened or better implemented. Awareness-raising among policymakers and provision of guidance on development of policies and legislation are needed.

### *Knowledge diffusion*

Knowledge gaps are a significant constraint to improving the management of microbial and invertebrate BCAs and microbial biostimulants – and need to be addressed. As well as promoting research, there is a need to promote the diffusion of knowledge to those who need it. This might, for example, involve support for an online knowledge portal featuring items such as relevant national policy frameworks and metrics of biological control impacts, or virtual communities of practice and associated multistakeholder innovation platforms (see below for more on networking). With regard to genetic improvement, options could include the development of tools such as a database on the genetic variation of populations potentially targeted for selection. Development of an inventory of microbial and invertebrate BCAs and microbial biostimulants used around the globe – including information on source countries, on countries, environments and production systems where they are used, and on target species – could be considered.

### *Cooperation and networking*

All aspects of the management of microbial and invertebrate BCAs and microbial biostimulants would benefit from improved cooperation and networking among stakeholders. Action in this regard might include, for example, supporting the establishment of networking platforms that facilitate the identification of expertise for country-level, regional or wider collaborative initiatives, including, in the case of classical biological control, the identification of collaborators in the region of origin of invasive pests. Other options could include stimulating the establishment and operation of research incubators, innovation hubs and working groups covering different aspects of biological control.

*Mainstreaming*

The use and conservation of microbial and invertebrate BCAs and microbial biostimulants are significant to many policy objectives and potentially affected by a range of different policies, including those addressing climate change, sustainable food systems (including agricultural pollution mitigation), One Health, and the conservation (including restoration) and sustainable use of biodiversity in general. They are relevant to many of the SDGs. There is a need to raise awareness of these links and to explore opportunities for mainstreaming the management of microbial and invertebrate BCAs and microbial biostimulants into such policies at all levels.

# Introduction

Increasing concerns about the impact of pesticide use on biodiversity and human health, and increasing demand for products from biodiversity-friendly production systems, including organic systems, have led to increasing interest in alternative methods of pest control, including the use of biological control agents (BCAs). A BCA is a living organism or virus that induces an action against target organisms that cause harm to humans or their resources (Van Driesche, Hoddle and Center, 2008; Heimpel and Mills, 2017; Stenberg *et al*., 2021). Similarly, interest is growing in the use biostimulants, which have been defined as "fertilising product[s] the function of which is to stimulate plant nutrition processes independently of the product's nutrient content with the sole aim of improving one or more of the following characteristics of the plant or the plant rhizosphere: (a) nutrient use efficiency, (b) tolerance to abiotic stress, (c) quality traits, or (d) availability of confined nutrients in the soil or rhizosphere" (du Jardin, 2015; European Union, 2019).

These interests have increasingly been reflected in the work of the Commission on Genetic Resources for Food and Agriculture (Commission). In 2019, the Commission adopted a Work Plan for the Sustainable Use and Conservation of Micro-organism and Invertebrate Genetic Resources for Food and Agriculture and chose microbial and invertebrate BCAs and microbial biostimulants to be among the categories of organisms to be addressed at its next session (FAO, 2019a).[1]

This paper presents an overview of the current status of BCAs and biostimulants (focusing only on microorganisms[2] and invertebrates) and their management, needs and challenge in terms of improving their management and potential opportunities for the Commission and its Members to contribute to efforts to address these needs and challenges. The scope covers all the sectors of agriculture as defined by FAO, i.e. crop and livestock production, forestry, fisheries and aquaculture.

Microbial and invertebrate BCAs provide natural biological control services across a wide range of terrestrial and aquatic environments used for crop and livestock production, forestry, fisheries and aquaculture and in those that are not used directly for these purposes but provide ecosystem services of importance to the food and agriculture sector (and often human well-being more generally). In many cases, they are also deliberately used to control species regarded as undesirable in the respective location, including because of environmental impacts. Deliberate use of microbial and invertebrate BCAs specifically against the pests, diseases and weeds directly impacting production is commonest in crop production (including forage crop production) and forestry. However, there are also applications in animal husbandry, including in the control of flies.

Implementation of biological control has resulted in positive contributions to sustainable food production and biodiversity and economic benefits for small farmers and consumers. A "systems approach" in which biological control is one of the main pest management methods used requires fewer fertilizer and pesticide inputs to prevent and reduce damage by pest animals, weeds and pathogens, leading to more sustainable food production (Bale, van Lenteren and Bigler, 2008). Reducing the overall use of chemical pesticides benefits biodiversity by lowering pressures on natural enemies and non-target organisms and by leaving less toxic residue in the environment (Hulot and Hillier, 2021). Creating spaces, for example around greenhouses, where biodiversity is able to flourish can improve the effectiveness of natural enemies (Messelink *et al*., 2021). Biological control has provided economic benefits to farmers by decreasing pesticide expenditures and increasing supply for the market, with consumers benefiting via lower food prices (Midingoyi *et al*., 2021). One example provided by Midingoyi *et al.* (2021) demonstrates that a biological control programme for management of cereal stemborers in East and Southern Africa lifted more than 137 000 people out of poverty each year over 20 years.

The paper is organized as follows. Chapter 1 introduces the main categories of biological control, providing a description of each type and an overview of the species involved, the production systems where they are significant, the benefits they provide,

[1] BCAs and biostimulants were grouped together because of the latter's significance in terms eliciting plants' natural defences against pests and diseases.

[2] Microorganisms are taken here to comprise bacteria, archaea, fungi (yeasts and moulds), algae, protozoa and viruses (Britannica, 2022).

the risks involved in their use, their state of adoption around the world, and needs and challenges related to their conservation and sustainable use. Chapter 2 addresses the status and trends of BCAs, providing an overview of their diversity, their risk status, the threats affecting them and the main knowledge gaps that need to be addressed on these topics. Chapter 3 addresses the state of management of BCAs, including the state of adoption and implementation of management activities such as breeding (genetic improvement) programmes and *in situ* and *ex situ* conservation. Chapter 4 addresses the state of adoption and implementation of policy and legal frameworks for the management of BCAs and the constraints involved in developing and implementing such frameworks. It includes a section on access and benefit-sharing (ABS). Chapter 5 addresses biostimulants, providing a description of their use and an overview of the species involved, the production systems where they are used, the benefits and risks involved in their use, the state of adoption of their use and of specific management practices, the state of policy and legal frameworks for their use, and challenges, needs and opportunities related to their use. Chapter 6 addresses options for the Commission, first considering the current state of the international institutional framework for the management of BCAs and biostimulants, both in terms of the international organizations involved in their management and in terms of existing guidance and tools, and then looking at the potential role of the Commission in improving the management of these components of biodiversity.

# Chapter 1. Types of biological control and extent of adoption

Biological control can be classified into four main categories depending on whether it is provided by biological control agents (BCAs) already present in the target environment, without human intervention (natural biological control) or with targeted human intervention (conservation biological control), or whether BCAs are introduced into the target environment for permanent (classical biological control) or temporary (augmentative biological control) establishment (Heimpel and Mills, 2017; Stenberg *et al.*, 2021). Biological control has been implemented worldwide; classical (importation) methods have been the most widely used, but the use of augmentative and conservation methods is now increasing (Mason, 2021). Implementation of classical biological control has slowed in recent years because of perceived risks (Collatz *et al.*, 2021) that have resulted in increased regulation (Barratt *et al.*, 2021). Adoption of biological control, particularly augmentative (van Lenteren, Bueno and Klapwijk, 2021) and conservation (Zaviezo *et al.*, 2021) methods, has become a preferred pest-management option because of the risks associated with chemical pesticides and a decline in the number of products available.

Use of biological control is increasing in regions with expanding economies, such as Latin America (van Lenteren *et al.*, 2020). However, uptake has been slow in some developing countries because of technological, dissemination, communication and extension challenges (Zhang and Chaudhary, 2021). Integrating biological control into pest management programmes is still challenging (Mills, 2021). Perception of biological control also remains an impediment, as media attention to poorly thought out past releases of species that have become invasive attracts the most interest from the public (Catton, 2021). However, there is optimism that incorporating broader contexts, such as the contribution of biological control to reducing the impacts of climate change (Heimpel and Wyckhuys, 2021) and integration of biological control into interdisciplinary community- and ecosystem-level management programmes (Mills, 2021), will enhance the contribution of biological control to sustainable food and agriculture on a global scale.

## 1.1 Natural biological control

Natural biological control is suppression of populations of pest or weed species by living organisms (or viruses) that occurs without the manipulation of humans. It is an ecosystem service that has been protecting humans from pests from time immemorial, at no cost, often without the knowledge of the humans themselves. In fact, it would be easy to argue that human societies could not have developed or flourished without natural biological control. It is only necessary to consider how much worse human diseases or crop destruction could have been throughout human history in the absence of the effects of predators limiting the population growth of disease-carrying mosquitoes (for example) or crop pests, or how much easier it would be for pests and weeds to invade new areas without the effects of resident predators, parasites and herbivores that constrain their establishment and spread. Natural biological control is included in the web of interactions that keeps populations of actually or potentially pestiferous microbes, animals and plants (weeds) from reaching damaging or outbreak levels. The critical importance of natural biological control underlines the necessity of conserving natural biodiversity, as this is the source of natural biological control.

Much of the research within the discipline of biological control has focused on approaches that involve human interventions (Sections 1.2, 1.3 and 1.4) rather than on natural processes that keep pest and weed populations low in the first place (Heimpel and Mills, 2017). However, natural biological control is very important both in preventing species from reaching pest status and in keeping known pest species at levels that are lower than they would otherwise be. Here, natural biological control is discussed briefly focusing on three topics: (i) how secondary pest outbreaks illustrate the importance of natural biological control; (ii) natural biological control as an ecosystem service; and (iii) how pest managers can take advantage of natural biological control to limit pesticide use.

### 1.1.1. Secondary pest outbreaks

Populations of previously innocuous species can be elevated to pest levels by the application of pesticides. This is known as a secondary pest outbreak, and it may seem paradoxical given that pesticides are applied in order to *reduce* rather than *increase* pest levels. However, secondary pest outbreaks are quite widespread, and they are enabled by the fact that many pest species are less susceptible and evolve resistance to pesticides more readily than their natural enemies do (Hardin *et al*., 1995). Thus, many pesticide applications fail to kill the pest but do kill their natural enemies.

The very existence of secondary pest outbreaks attests to the role of natural biological control in suppressing pest populations. Secondary pest outbreaks show that arthropods that are either undetected or innocuous can erupt to pest status once their natural enemies are removed. Many examples of secondary pest outbreaks can be found in the biological control literature (Luck, van den Bosch and Garcia, 1977; Heimpel and Mills, 2017). For example, the use of fungicides to control late blight in potatoes can lead to aphid outbreaks, as the fungicides kill entomopathogenic fungi that otherwise keep aphid populations in check (Lagnaoui and Radcliffe, 1998). Luck, van den Bosch and Garcia (1977) concluded that problems associated with 24 of the 25 main agricultural pest species in California during the 1970s were exacerbated by secondary pest outbreaks and pest resurgences (a related phenomenon). In another classical example, Settle *et al.* (1996) showed that insecticide use in Southeast Asian rice paddies increased pest problems by disrupting natural-enemy populations.

### 1.1.2. Natural biological control as an ecosystem service

Natural biological control is considered an ecosystem service, and a number of attempts have been made to quantify its monetary benefits to human societies. In a global analysis, Costanza *et al.* (1997) estimated a value of over USD 400 billion/year for marine and terrestrial ecosystems combined (see also Pimentel *et al*., 1997). For the more limited case of the suppression of native insects in the United States of America, Losey and Vaughan (2006) estimated a value of USD 4.5 billion/year in increased crop yields and reduced control costs. To these economic benefits must be added the human-health and environmental benefits that result from the reduction of pesticide use, which include reductions in greenhouse-gas (GHG) emissions associated with the manufacture and application of the pesticides (Heimpel and Wyckhuys, 2021). As an example, naturally occurring predatory insects such as ladybird beetles led to a five-fold reduction in insecticide applications against the soybean aphid in the Midwestern United States of America (Landis *et al*., 2008), which translates into an estimated reduction of over 200 million kg of GHG emissions per year in the region (Heimpel *et al*., 2013). Rosenheim *et al.* (1997) similarly found that natural biological control by predatory and parasitic insects prevented the cotton aphid from reaching pest status during most years and at most sites in the Central Valley of California. In the realm of weed biological control, a number of studies have demonstrated that native herbivores can greatly limit the spread and population growth of introduced thistles (Guretzky and Louda, 1997; Eckberg, Tenhumberg and Louda, 2014).

### 1.1.3. Taking advantage of natural biological control

While natural biological control itself does not involve manipulation of BCAs or their environments, it is possible for pest managers to take advantage of natural biological control interactions. First, they can enhance the power of these interactions through habitat manipulation. This is the realm of conservation biological control (Section 1.2), and it can take the form of strategies such as increasing the vegetational diversity of agricultural habitats or reducing the use of broad-spectrum pesticides in a directed effort to favour BCAs (Heimpel and Mills, 2017; Zaviezo *et al*., 2021).

Second, information on the role that natural enemies play in reducing pest populations can be used to increase the recommended threshold density at which pesticides should be applied. Decisions on the use of pesticides are often based on the abundance of the pests themselves, with recommendations to apply pesticides only when pest densities exceed a scientifically based “action threshold”. These thresholds are typically calculated without considering the role of natural biological control. Including the role of biological control in naturally suppressing pest populations in action thresholds can lead to substantial reductions in pesticide applications, as the thresholds are elevated during times of high biological control activity. As an example, recommendations for the application of insecticides against the tomato fruitworm (a caterpillar) have traditionally been based on the number of fruitworm eggs found per tomato leaf, with treatment recommended when this number exceeds a particular threshold. Research on the relationship between parasitism of these eggs by resident Trichogramma wasps and tomato damage allowed the development of a modified threshold that takes the parasitism into account. As unparasitized tomato fruitworm eggs are white, while parasitized eggs are black, more white eggs can be tolerated without spraying as the ratio of black to white eggs increases (Hoffmann *et al.*, 1990). Similar relationships have been developed for other pests, including predatory mites, aphids and caterpillars other than the tomato fruitworm (Flint and Dreistadt, 1998; Walker *et al.*, 2010; Hallett *et al.*, 2014).

## 1.2 Conservation biological control

### 1.2.1. Definition and description

Conservation biological control is an approach that encompasses a diverse set of practices that aim to preserve and enhance the activity of natural enemies to improve existing levels of pest control and thereby reduce the negative effects of harmful species (Eilenberg, Hajek and Lomer, 2001; Heimpel and Mills, 2017). These tactics can be grouped into four main categories: habitat/vegetation manipulation; crop management practices; direct provision of resources; and thoughtful pesticides use in conventional agriculture.

Habitat or vegetation manipulation is probably the best known and most intensively used tactic within conservation biological control. Many different practices can fall into this category, ranging in temporal scale (from within season to several years of crop rotations) and in spatial scale from (field to landscape) (reviews by Barbosa, ed., 1998; Gurr, Altieri and Wratten, eds., 2004; Gurr *et al.*, 2017; Peñalver-Cruz *et al.*, 2019; Holland *et al.*, 2020; Zaviezo *et al.*, 2021). However, they all seek a common goal, which is to diversify vegetation in order to provide natural enemies with resources not provided by the crop, either throughout the year or at specific times or seasons. These resources may include refuge from crop disturbances, specific microclimatic conditions, alternative prey or additional non-prey food (e.g. pollen and nectar) (Landis, Wratten and Gurr, 2000; Tscharntke *et al.*, 2005; Gurr *et al.*, 2017; Peñalver-Cruz *et al.*, 2019). These alternative or complementary resources should improve natural enemies' survival, reproduction, immigration and permanence, which in turn should result in an increase in their effectiveness in controlling pests (Zaviezo *et al.*, 2021).

In many cases, vegetation management practices are carried out in order to maintain a diversified community of local natural enemies, particularly generalist predators or plant pathogen antagonists, that can maintain low pest populations or quickly colonize the crop when there are pest outbreaks (Finke and Snyder, 2008, 2010; Woltz and Landis, 2013; Crowder and Jabbour, 2014; Costamagna, Venables and Schellhorn, 2015; Jonsson, Kaartinen and Straub, 2017; Zaviezo *et al.*, 2021). The theoretical support for the better performance of diversified communities of natural enemies comes from biodiversity–ecosystem function theory (Hooper *et al.*, 2005), the "insurance hypothesis" or "portfolio effect" (Naeem, 1998; Yachi and Loreau, 1999; Finke and Snyder, 2010) and the sampling or species identity effect (Cardinale *et al.*, 2006; Straub and Snyder, 2006; Finke and Snyder, 2010; Maas *et al.*, 2015). Nevertheless, there are cases in which vegetation management targets specific species of natural enemies (mostly specialist parasitoids in the orders Hymenoptera and Diptera) with very particular requirements, such as sugars (Jervis *et al.*, 1993; Steppuhn and Wäckers, 2004; Lundgren, 2009) or alternative hosts (e.g. Peñalver-Cruz *et al.*, 2020). As many parasitoids obtain clear benefits from sugar meals and they can be found using nectar under natural conditions, Heimpel and Jervis (2005) proposed the "nectar provision hypothesis", which postulates that biological pest control by parasitoids can be enhanced by providing nectar in the vicinity of crops, as modern crops and agroecosystems do not provide enough naturally occurring sugar sources.

The second category is crop management practices (cultural practices) other than vegetation management. These include soil management practices, which are particularly relevant for soil entomopathogens and plant pathogen antagonists, although for this to be consistently effective, detailed knowledge of species biology, and sometimes whole microorganism communities, is needed. Nevertheless, there are some soil management practices that have been studied and whose effects on pest control have been documented. For example, increasing relative humidity by modifying crop irrigation techniques or regimes or through other crop-management practices can increase fungal activity (Pell, Hannam and Steinkraus, 2010). Regarding soil disturbances, reduced till or no-till practices have been found to favour soil-dwelling entomopathogens in several crops, although this may be mediated by host abundance (Meyling and Eilenberg 2007; Pell, Hannam and Steinkraus, 2010). Burning crop residues is thought to negatively affect microorganisms, both in crop residues and in the soil, while mulching may favour them by increasing organic matter and humidity, and also benefit some soil predators (Stirling, Halpin and Bell, 2011; Timper, 2014).

The third main category of conservation biological control is direct provision of resources. This can vary greatly, ranging from the provision of sugar sprays for parasitoids to the provision of protein sources or pollen for arthropod predators, the addition of organic amendments to soil for microorganism antagonists (Timper, 2014) and provision of shelters for predatory mites, birds or bats (Jacob and Evans 1998; Wade *et al.*, 2008; Brown, de Torrez and McCracken, 2015; Puig-Monstserrat *et al.*, 2015; Beltrà *et al.*, 2017; Pekas and Wäckers, 2017). Nevertheless, the cost-effectiveness of these practices has not been very well documented (Wade *et al.*, 2008). In the past, commercial "food sprays" have been formulated, but these are very rarely used in agricultural production (Wade *et al.*, 2008; Broufas and Pappas, 2016).

Pesticides have severe negative impacts on natural enemies, and more thoughtful pesticide use, particularly in conventional agriculture, could help reduce both lethal and the non-lethal effects on them (Gurr, Altieri and Wratten, eds.,2004; Torres and Bueno, 2018). Options include using selective or specific products, appropriate timing of pesticide application, reducing application rates or areas, using specific formulations or methods, and using pesticides with low persistence (Hajek, 2004; Gurr, Altieri and Wratten, eds., 2004; Torres and Bueno, 2018; Zaviezo *et al.*, 2021). The approach is relevant for arthropod natural enemies, entomopathogens and plant pathogen antagonists, but by far the bulk of research is on the first of these three groups (Mietkiewski, Pell and Clark, 1997; Klingen and Haukeland, 2006; Meyling and Eilenberg, 2007; Pell, Hannam and Steinkraus, 2010; Timper, 2014).

Where selective pesticides are concerned, a key issue is the ability to determine negative impacts on the relevant natural enemy species. In arthropods, this has been traditionally done by measuring mortality (e.g. LC50) in laboratory bioassays (Hassan *et al.*, 1985; Hassan, ed., 1992). The International Organization for Biological Control (IOBC) recommends a tiered approach (or sequential testing scheme), starting with laboratory assays and, depending on the results, moving to semi-field or field experiments (Hassan *et al.*, 1985; Hassan, ed., 1992; Candolfi *et al.*, 2000). The IOBC also suggests a classification of pesticides into four categories according to the level of mortality or reduction in performance of natural enemies (harmless, slightly harmful, moderately harmful and harmful) (Hassan, ed., 1992; Candolfi *et al.*, 2000). However, there is some criticism of the threshold levels used, with slightly harmful corresponding to a 30–79 percent, and moderately harmful to an 80–98 percent, mortality or reduction in beneficial capacity in laboratory experiments (Hassan, ed., 1992). Assessing non-lethal effects of pesticides (e.g. on reproduction, progeny sex ratio, developmental time or foraging behaviour) is important, particularly with newer reduced-risk pesticides that are less likely to produce acute toxicity (Desneux, Decourtye and Delpeuch, 2007; Stark, Vargas and Banks, 2007; Torres and Bueno, 2018). The IOBC has developed a database of selectivity[3] that covers the effects of more than 200 pesticides (insecticides, acaricides, fungicides, entomopathogens and others) on more than 110 species of beneficial arthropods and insect pathogens based on studies performed since 1983, and keeps incorporating more.

### 1.2.2. Species and production systems involved and examples of successes and failures

As mentioned earlier, many conservation biological control tactics do not target specific BCAs or specific production systems, particularly those applied at larger spatial and temporal scales. In the case of vegetation management at field or plot levels, targets and systems are very diverse, especially where polyculture and intercropping are concerned (Martin-Guay *et al.*, 2018). Cover crops are more common in orchards and perennial crops, for example citrus orchards (Gómez-Marco, Urbaneja and Tena, 2016), tea plantations (Chen *et al.*, 2019a, 2019b), olive orchards (Gómez *et al.*, 2018) and vineyards (Daane *et al.*, 2010). In the case of companion plants, a successful example developed in California and replicated in many regions is the use of alyssum (*Lobularia maritima*) in lettuce crops to attract hoverflies (Syrphidae) that control aphids (Brennan, 2013).

Most adjacent vegetation management studies relate to generalist predators and their use of such habitats (e.g. MacLeod *et al.*, 2004; Carrié, George and Wäckers, 2012; Hatt *et al.*, 2017), but in most cases pest suppression has not been documented in the crop. Successful examples include grass strips and beetle banks in cereal crops in Europe (Collins *et al.*, 2002; Holland *et al.*, 2020), flower strips in oilseed rape (Sutter, Albrecht and Jeanneret, 2017) and potatoes (Tschumi *et al.*, 2016) in Europe, native perennial flowering plants in blueberries in the United States of America (Blaauw and Isaacs, 2015) and flowering plants in rice fields in Thailand, China and Viet Nam (Gurr *et al.*, 2016). In the case of conservation biological control by entomopathogens, emphasis has been given to aphid control with Entomophthorales fungi (Meyling and Eilenberg 2007). Natural-enemy diversity and biological control have also been studied at the landscape scale (Bianchi, Booij and Tscharntke, 2006; Tscharntke *et al.*, 2008; Shackelford *et al.*,

[3] Available through https://www.iobc-wprs.org/restricted_member/toolbox.cfm

2013; Grez *et al.*, 2014; Landis, 2017; Perović *et al.*, 2018; Martin *et al.*, 2019). Several landscape studies have targeted the control of aphids by coccinellids (e.g. Elliott, Kieckhefer and Beck, 2002; Gardiner *et al.*, 2009; Grez, Zaviezo and Gardiner, 2014; Plećaš *et al.*, 2014).

In the case of food supplements, a review carried out in 2008 showed that by far the most commonly studied BCAs were species in the order Neuroptera, followed by Coleoptera, parasitic Hymenoptera and Hemiptera, and that the most commonly studied pests were Lepidoptera (Wade *et al.*, 2008). The provision of pollen has also been studied and applied in production systems using phytoseiid mites (van Rijn and Tanigoshi, 1999; Duarte *et al.*, 2015; Pijnakker *et al.*, 2016).

In livestock production, flies and some other pests can also be targets for conservation biological control. Immature stages of flies can be attacked by several natural enemies, including parasitoids (e.g. the hymenopteran species *Muscidifurax raptor* and *Spalagia endius*) and predators (e.g. the mite *Macrocheles muscaedomesticae* and histerid beetles such as *Carcinops pumilio*) (reviewed by Geden *et al.*, 2021). In confined animal production, leaving some manure residues within the facilities can help conserve these natural enemies (Mullens *et al.*, 2001). In more extensive production systems, dung beetles (Coleoptera: Scarabidae) are typically considered BCAs of fly species because they compete with them for food resources (Nichols *et al.*, 2008; Jones *et al.*, 2019; Brewer *et al.*, 2021).

### 1.2.3. Benefits and risks

Apart from not achieving the desired pest control, there are very few risks in conservation biological control. The most important risk could be that the target pest, or other pests, might benefit from the vegetation manipulation, lower pesticide use or provision of food and shelter (e.g. Lavandero *et al.*, 2006; Daane *et al.*, 2010; Leman and Messelink, 2015). Also, when practices favour multiple natural enemy species, one (or more) of the species could potentially interfere with another that suppresses pests more efficiently, thus resulting in less pest suppression. Such antagonistic interactions among natural enemies might occur through consumptive or non-consumptive effects (i.e. predation or behavioural modification). In this context, the most studied interaction is intraguild predation, which occurs when natural enemies sharing a prey engage in predatory interactions among themselves (Polis, Myers and Holt, 1989; Rosenheim *et al.*, 1995; Snyder and Ives, 2003; Vance-Chalcraft *et al.*, 2007).

On the other hand, there are many potential additional benefits. In the case of vegetation diversification for example, these may include benefits in terms of biodiversity conservation, including of wild pollinators (Wratten *et al.*, 2012; Steward *et al.*, 2014; Garibaldi *et al.*, 2018), aesthetic value for agritourism and cultural significance of the plants or their related animal species for local populations.

### 1.2.4. Extent of adoption and differences between regions

The extent of adoption of conservation biological control is very hard to assess because many practices are not documented and because they may be carried out with multiple purposes and vary greatly from year to year. A recent review concluded that “on a global scale the best examples of conservation biological control strategies have been implemented to control pests of rice in Asia (Gurr *et al.*, 2016; Settele and Settle, 2018; Ali *et al.*, 2019), maize and sorghum in Africa (Khan *et al.*, 2000), apples in Europe (Happe *et al.*, 2019) and North America (Bostanian and Lasnier, 2007), cotton in North America (Steinkraus, 2007) and in vineyards in New Zealand (Gurr *et al.*, 2006)” (Zaviezo *et al.*, 2021). Most research has been concentrated in Europe and North America, so it is a challenge to document, as well as to develop and successfully implement, conservation biological control in the developing world. It is estimated that there are about 510 million small farms worldwide, mostly concentrated in less-developed countries (Lowder, Sánchez and Bertini, 2021). In this respect, the recent reviews by Wyckhuys *et al.* (2013) for the developing world and Peñalver-Cruz *et al.* (2019) and van Lenteren and Cock (2020) for South America are very welcome. For the developing world, most research literature relates to habitat management (plant diversification) and focuses on Brazil, China or Cuba, with rice, maize and cotton being the crops most commonly targeted. Interestingly, there are few or no records for several key staple crops, some originating in these same regions (Wyckhuys *et al.*, 2013). In South America, the main overall tactics implemented relate to plant diversification (e.g. intercropping and agroforestry) and management of non-crop vegetation (e.g. use of insectary plants).[4] Some of these tactics date from pre-Inca times, but there has been little evaluation of effects on pest control in this region (Peñalver-Cruz *et al.*, 2019; van Lenteren and Cock, 2020).

[4] Insectary plants are plants that attract insects.

### 1.2.5. Needs and challenges for further adoption

Even though understanding of pest and natural-enemy ecology and interactions at field and landscape levels has improved, particularly for arthropods, the biggest challenge for conservation biological control is that the comprehensive agroecosystem knowledge that would allow the approach to be applied in a consistent and cost-effective way is still lacking. In a few cases, a good part of this knowledge exists, but it is very context-specific and therefore not transferable to other locations, pests or crops (Holland *et al.*, 2020). Nevertheless, as knowledge is gained and new technologies appear, recommendations for management practices are improving.

Particular topics where more research is needed include the following:

- ecology of microorganisms, both as target pests and as BCAs (Meyling and Eilenberg, 2007; Pell, Hannam and Steinkraus, 2010; Timper, 2014).
- conservation of arthropod and microbial natural enemies in soil environments (Campos-Herrera, El-Borai and Duncan, 2015);
- effects of food supplements (do they act as food, attractant or arrestant?) and ways of delivering them (when, where, how?) (Wade *et al.*, 2008);
- effects of adjacent vegetation on pest control, and not just on natural enemy abundance (Holland *et al.*, 2020);
- negative effects (dis-services) of vegetation diversification (Gillespie and Wratten, 2017; Shields *et al.*, 2019); and
- the effect of landscape composition and heterogeneity on biological control, and not just on the conservation of the taxonomic and functional diversity of natural enemies (Martin *et al.*, 2019).

There are also economic challenges (Shields *et al.*, 2019), for example related to the cost of actions such as establishing and maintaining non-crop vegetation, delivering supplementary resources or using more expensive selective pesticides. Benefits in terms of yield, produce quality or income need to be demonstrated and the information conveyed to farmers (Naranjo, Ellsworth and Frisvold, 2015; Chaplin-Kramer *et al.*, 2019; Holland *et al.*, 2020).

Sociological challenges (Shields *et al.*, 2019) include the fact that conservation biological control tactics are knowledge dependent and "more complicated" than pesticide application. Tactics at the landscape scale require collaboration on the part of many farmers (Geertsema *et al.*, 2016). Moreover, many farmers are risk adverse in their decision making (Tracey, 2014) or grow high-value crops where even cosmetic damage is not acceptable (Hajek, 2004). Another issue is the need to improve communication between scientists and farmers and among farmers themselves (Barratt *et al.*, 2018; Wyckhuys *et al.*, 2018a; Shields *et al.*, 2019).

## 1.3 Classical biological control

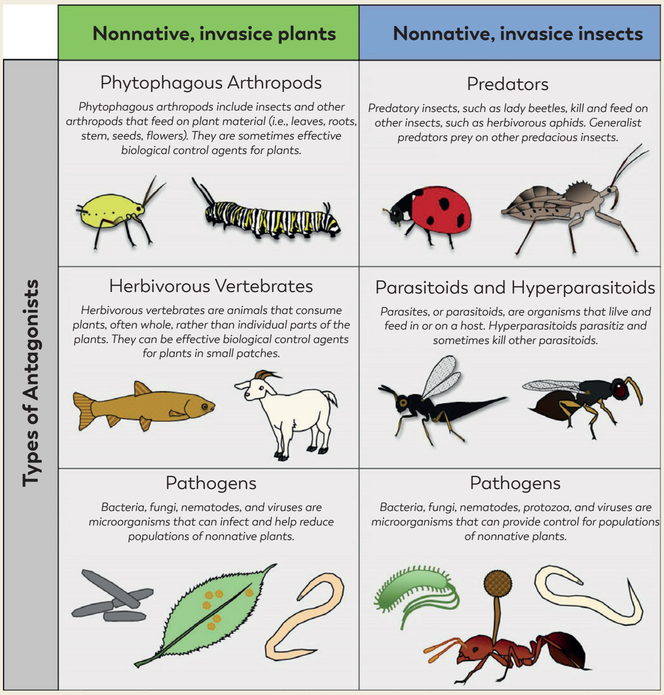
### 1.3.1. Definition and description

Classical biological control, also referred to as introduction or importation biological control, is the intentional introduction, release and establishment of specialist natural enemies (see below for examples) in areas where they did not previously exist for the suppression of damaging populations of non-native invasive terrestrial arthropod pests (insects and mites), weeds or, in rare cases, vertebrate pests (e.g. rabbits) (Sheppard *et al.*, 2019). This process of introducing natural enemies into new areas for pest control is referred to as "classical", as it was the first successful method (see example below for cottony cushion scale, *Icerya purchasi*) of using natural enemies for control of invasive pests. Supporting methodology and underlying theory were subsequently refined over a long period of time.

### 1.3.2. Species used, production systems where used and examples of successes and failures

The targets for classical biological control are organisms that have been accidentally or deliberately introduced into areas outside their native ranges and have become invasive pests that cause significant economic, environmental or human/animal/plant health problems. Recognition of these problems can lead stakeholder groups that are adversely affected by the invasive pest to initiate exploratory discussions with regulatory agencies to determine the feasibility of developing a classical biological control programme targeting the pest. If such a programme is to be developed, consensus is needed across all potentially affected parties, and there may be a need to discuss the environmental, economic and social impacts that may arise (Sheppard *et al.*, 2019).

**Figure 1. Five major types of antagonists that may affect non-native, invasive plants and insects**




*Source*: Schultz, A.N., Lucardi, R.D. & Marisco, T.D. 2019. Successful invasions and failed biocontrol: The role of antagonistic species interactions. *BioScience*, 69: 711–724. Reproduced by permission of Oxford University Press on behalf of the American Institute of Biological Sciences.

Problems caused by non-native species may occur because high-density populations have developed as a result of unregulated population growth and spread. This may be due to a lack of top-down population-level regulation by upper trophic-level organisms that use the pest as food (Hoddle *et al.*, 2021). When a pest is introduced into an area where it did not previously exist, it may become dissociated from its natural enemies. This may be a key reason why non-native organisms frequently exhibit unregulated population growth when they enter a new area. The mechanism that releases the high population growth is referred to as "enemy escape", as the pests have "escaped" partially or fully from the mortality imposed by their natural enemies (Keane and Crawley, 2002; Torchin *et al.*, 2003; Schultz, Lucardi and Marisco, 2019). Classical biological control aims to rebuild associations between pests and coevolved, host-specific natural enemies and thereby reduce abundant invasive pest populations to less-damaging levels.

Natural enemies commonly used in classical biological control programmes for arthropods fall into three general categories: predators, parasitoids, and pathogens. Weed biological control programmes tend to use mostly herbivorous insects and mites, and occasionally plant pathogens (Schultz, Lucardi and Marisco, 2019) (Figure 1).

Natural enemies are most often sourced from the native range of the target pest. This process of surveying the native range for natural enemies is referred to as foreign exploration. If a target pest has already been the subject of a classical biological control programme, natural enemies may already be known, well-studied and available to be "borrowed" from cooperating scientists for importation into a quarantine facility for safety testing (see below for more details on risk assessment) and potential release and establishment in a new area.

Natural enemies used in classical biological control programmes have included predators, such as the coccinellid beetle, *Novius cardinalis* (formerly known as *Rodolia cardinalis*) imported for the control of the sap-sucking citrus pest *I. purchasi* (Caltagirone and Doutt, 1989). This was the first attempt at controlling an invasive agricultural pest insect with an imported predator. This highly successful programme, conducted in 1888–1889, is credited with saving the emerging citrus industry in California, and *N. cardinalis* is still an important natural enemy in the California citrus ecosystem. *N. cardinalis* has also been used to control *I. purchasi* in the Galápagos Islands, where the goal was conservation of endemic and indigenous plants that were being killed by uncontrolled, high-density *I. purchasi* populations (Hoddle *et al.*, 2013).

Predators typically consume more than one prey item to complete their development and therefore need relatively high pest densities to develop into adults. Parasitoids, in contrast to predators, utilize a single host for development. Feeding by the parasitoid larva(e) kills the host. Examples of parasitoids used in successful biological control projects include parasitic Hymenoptera, such as *Cosmocomoidea ashmeadi* (formerly known as *Gonatocerus ashmeadi*), which parasitizes eggs of the cicadellid pest *Homalodisca vitripennis* (formerly known as *H. coagulata*). This parasitoid provided rapid and impressive control of *H. vitripennis* in French Polynesia (Grandgirard *et al.*, 2009).

Pathogens used as natural enemies of insects include fungi, viruses, bacteria and nematodes, and are collectively referred to as entomopathogens. Examples of entomopathogens include a fungus (*Entomophaga maimaiga*) (Hajek, 1999) and a virus (*Lymantria dispar* multicaspid nuclear polyhedrosis virus [LdMNPV]) (Murray and Elkinton, 1989) that were used for biological control of an invasive insect forest pest, the gypsy moth (*L. dispar dispar*), in the northeastern United States of America.

Various species of plant pathogens have been used against invasive weeds (Morin, 2020), but perhaps the most well-known example of successful weed biocontrol involves not a plant pathogen but two species of insect, a moth, *Cactoblastis cactorum*, and a scale insect, *Dactylopius opuntiae*, which were imported into Australia, where they successfully controlled invasive weedy *Opuntia* spp. cacti, which are native to South America (Goeden and Andrés, 1999; Hoffman *et al.*, 2020). Initially, *C. cactorum* was credited with providing control of *Opuntia* spp. in Australia. However, studies from South Africa, where both species of insect were introduced from populations in Australia for control of weedy non-native *Opuntia* spp., suggest that *D. opuntiae* and not *C. cactorum* may be the species of natural enemy most responsible for suppressing the cactus populations (Hoffman *et al.*, 2020). A similar comparative study in Australia is needed to confirm the conclusion of Hoffman *et al.* (2020) that *D. opuntiae* is responsible for suppressing *Opuntia* spp. in Australia.

Global and regional catalogues listing natural enemies and their target arthropod pests (Cock *et al.*, 2016; Van Driesche *et al.*, 2018) and weeds (Winston *et al.*, eds., 2014) are available.

### 1.3.3. Success rates, benefits and risk assessment

Natural enemies used in classical biological control programmes have had varying levels of "success" when impacts are measured in terms of suppressing target pest populations to less-damaging levels. For releases of arthropod natural enemies against insect pests infesting woody and herbaceous plants, analysis of BIOCAT, a global database for classical biological control programmes, indicated that 33 percent of natural enemy introduction events resulted in establishment. Of those established introductions, 10 percent resulted in satisfactory control of the target pest (Kenis *et al.*, 2017). Success rates tended to be higher in perennial ecosystems comprised of woody plants (e.g. against tree pests in forests and orchards), presumably because of the long-term stability of these systems (ibid.). A similar analytical study, which focused on insect biological control in North America between 2005 and 2018, indicated that 54 percent of the 208 parasitoid species released established and the target pests were fully or partially controlled in 28 percent of examined cases (Van Driesche *et al.*, 2020). With respect to the use of entomopathogens and nematodes for control of pest insects, of those agents that established following release, 51 percent resulted in complete suppression of the target pest and 36 percent provided partial control (Hajek, Gardescu and Delalibera, 2021). For weed BCAs, about 24 percent of programmes have resulted in heavy damage to targets (Schwarzländer *et al.*, 2018). Examples of successes and failures of biological control programmes that have been initiated globally are documented by Day *et al.* (2021), McClay *et al.* (2021), Moran, Zachariades and Hoffmann (2021), Schaffner, Knapp and Seier (2021), van Lenteren *et al.* (2021), Witt *et al.* (2021) and Wyckhuys *et al.* (2021).

When successful, classical biological control programmes provide self-sustaining pest control over vast areas: achievements that other management strategies, such as the use of insecticides or herbicides, are unable to match given their high financial costs and the negative ecological impacts of widespread repeated pesticide applications (Van Driesche, Hoddle and Center, 2008). The economic returns on successful biological control programmes can be highly positive. For example, Naranjo, Ellsworth and Frisvold (2015) report benefit–cost ratios ranging from 5:1 to > 1 000:1. Zeddies *et al.* (2001) calculated that the cost–benefit ratios for the biological control of the cassava mealybug (*Phenococcus manihoti*) over a 40-year period in 27 African countries were between 97:1 and 800:1. Van Wilgen and De Lange (2011) compared the costs of weed biological control research and implementation in South Africa to the benefits of restored ecosystem services, or avoided costs, and avoided ongoing control costs; biological control was found to be extremely beneficial in economic terms, with estimated benefit–cost ratios ranging from 8:1 to 3726:1. Successful biological control can lift of farmers out of poverty as production becomes more profitable because of reduced expenditure on pest control (Midingoyi *et al.*, 2021). Although there are failures, it is considered that the high returns obtained when projects are successful more than compensate for the cost of investment in failed projects (Naranjo, Ellsworth and Frisvold, 2015; Naranjo, Frisvold and Ellsworth, 2019).

Natural enemies collected during foreign exploration expeditions are subjected to safety testing either in a secure quarantine facility or in their country of origin to determine whether they pose any unacceptable risks to non-target species in areas where releases are proposed or into which natural or human-assisted spread is anticipated. Safety tests attempt to determine a natural enemy's host range (i.e. the number of non-target species the natural enemy can use to complete development) and host specificity (i.e. the natural enemy's host use preferences) through experiments that may either give natural enemies a "choice" of species to attack (choice tests) or just a single species to attack (no-choice tests). Data on rates of attack and successful development are compared to control data derived from natural-enemy use of the target pest species.

Ideally, quarantine tests identify safe natural enemies as species that have a narrow host range (i.e. attack just the target pest and a few non-target species at low levels) and high levels of host specificity (i.e. preferentially attacks the target pest when simultaneously given a choice of non-target species to attack) (Messing and Brodeur, 2018). Guidelines on selecting non-target species for exposure studies to natural enemies in quarantine are available (Kuhlmann, Schaffner and Mason, 2006; van Lenteren *et al.*, 2006; Barratt, Todd and Malone, 2016), as are guidelines for evaluating the host ranges and host specificity of natural enemies for use in classical biological control programmes (Van Driesche and Reardon, eds., 2004; Bigler, Babendreier and Kuhlmann, 2006; van Lenteren *et al.*, 2006). Suggested steps for developing a programme, and a detailed overview of regulatory frameworks, where they exist, are provided by Sheppard *et al.* (2019). Host-range and host-specificity testing data are used to develop non-target risk assessment evaluations that are assessed by regulatory agencies to determine the "safety" of natural enemies under consideration for release.

The current design of host use experiments in quarantine promotes selection of BCAs that have high levels of host specificity and narrow host ranges so as to minimize risk to non-target species. This attention to reducing threats to non-target species has always been emphasized for BCAs used against weeds but is relatively new (since the 1990s) for arthropod biological control (Heimpel and Cock 2018; Hoddle *et al.*, 2021). There have been several notable cases of classical BCAs causing damage to native insect and plant populations, sometimes at significant levels (Louda *et al.*, 2003; Van Driesche and Hoddle, 2017a). However, recent analyses strongly suggest that for arthropod and weed biological control the selection of host-specific natural enemies has increased significantly (Van Driesche and Hoddle, 2017b; Hinz, Winston and Schwarzländer, 2019). For classical weed biological control, the vast majority of BCAs introduced (more than 99 percent) have had no known significant adverse effects on non-target plants (Suckling and Sforza, 2014).

### 1.3.4. Regional differences

Australia, Canada, New Zealand, South Africa and the United States of America all have well-developed classical biological control programmes for arthropod pests and weeds. In Europe, France, Greece, Italy and Spain have significant introduction biological control programmes targeting arthropod pests (Schaffner, Knapp and Seier, 2021) These countries are generally relatively wealthy, have made considerable investments in infrastructure (e.g. quarantine facilities) and personnel (i.e. scientists trained in biological control) and have had significant invasive pest problems associated with croplands, rangelands and natural areas.

Interestingly, western European countries have not invested as significantly in classical weed biological control programmes, despite having significant problems with invasive plants (Shaw *et al.*, 2018). For example, the United Kingdom of Great Britain and Northern Ireland released its first natural enemies as part of a classical biological control programme targeting Japanese knotweed, *Fallopia japonica* var.

*japonica*, in 2010 (Shaw *et al.*, 2018). The Centre for Agriculture and Bioscience International (CABI), which has significant institutional holdings in Europe (e.g. Switzerland and the United Kingdom), supports the development of classical biological control programmes in many countries outside western Europe.

Countries where there is a need for classical biological control of invasive pests are plentiful. For example, invasive weeds and arthropod pests cause annual losses amounting to trillions of US dollars across African countries collectively (Eschen *et al.*, 2021), and there is a clear need for a continent-wide or a pan-African response to managing these problems (Sileshi, Gebeyehu and Mafongoya, 2019). The importance and utility of biological control for the management of invasive pests in Africa has been recognized (Neuenschwander, 2010), and there have been some very successful programmes targeting insects (e.g. cassava mealybug, *Phenococcus manihoti* [Bellotti, Herrera Campo and Hyman, 2012]) and weeds (Moran, Hoffmann and Hill, 2011). The highly publicized invasion of Africa in 2016 by the fall armyworm, *Spodoptera frugiperda*, which caused significant crop losses across many African countries (Day *et al.*, 2017), may be increasing interest in understanding of and support for classical biological control in Africa. This pest is now under consideration as a target for a classical biological control programme (Tepa-Yoto *et al.*, 2021), as is another highly damaging agricultural pest, the tomato leafminer *Tuta absoluta* (Aigbedion-Atalor *et al.*, 2020).

Some successful classical biological control programmes have also been reported in the Near East and in much of Asia. A recent review shows that the use of biocontrol against insect pests in Latin America is increasing steadily, although weed biological control is still very limited (van Lenteren *et al.*, eds., 2020). China is one country in Asia that is increasing efforts in classical biological control of invasive pests, which cost the country an estimated USD 18 billion annually (Wan and Yang, 2016). Invasive weeds (Zhu *et al.*, 2020) and insects (Wan and Yang, 2016) have both been identified as potential targets for classical biological control. To support biological control programme development and researcher training, research laboratories in China have developed extensive collaborative programmes with scientists in the United States of America targeting insect pests (e.g. spotted lantern fly, *Lycorma delicatula* [Xin *et al.*, 2020]) and invasive weeds [Ding *et al.*, 2006]) that are problematic in the United States of America. Across these regions, there are many opportunities to develop programmes that would be likely to be highly successful if they were well designed and funded and appropriate targets selected.

### 1.3.5. Needs and challenges for further adoption

Reciprocity in classical biological control is necessary if collaborative programmes and ongoing cooperative efforts are to be successful over the long term. In this regard, one area needing improvement is ABS treaties and laws (Section 4.5). In some instances, these treaties can result in asymmetric sharing of natural enemies. For example, an "importing" (receiver) country that readily takes natural enemies from "exporting" (provider) countries that have generous legislation that allows international movement of natural enemies intended for use in "public good" projects may have "biodiversity protection" legislation that restricts, or entirely prevents, reciprocal flow of natural enemies to the provider countries. Such situations, when they exist, need to be corrected to ensure equitable exchange agreements.

Despite well-recognized benefits (i.e. permanent pest control over large areas and high benefit–cost ratios), and even though the number of invasive species establishing in new areas is increasing (Seebens *et al.*, 2017), investment (i.e. number of projects and scientists and amount of funding) in classical biological control of arthropods and weeds is declining in some countries (Messing and Wright, 2006; Warner *et al.*, 2011; Messing and Brodeur, 2018). This decline, especially in the United States of America, is due, in part, to a diminishing number of highly trained scientists that specialize in classical biological control, old or oversubscribed supporting infrastructure (e.g. quarantine facilities), lack of financial support for multi-year projects (i.e. those lasting longer than five years), and increasing regulatory hesitancy over perceived potential risks associated with releases of natural enemies in new areas (Hoddle *et al.*, 2021; Messing and Wright, 2006; Van Driesche, Winston and Duan, 2020; Warner *et al.*, 2011).

In conclusion, classical biological control is a highly applied, pragmatic, cost-effective approach to invasive pest management. This method of pest population suppression has a proven beneficial track record in terms of ecological, economic and social impacts, and overall safety (Heimpel and Cock, 2018). It has strong underlying theoretical and practical foundations that result from decades of applied field experimentation and evaluation. There is huge global potential for continued development and application of classical biological control programmes targeting invasive pests, some of which are common problems across several countries and would be amenable to collaborative international efforts (e.g. cassava mealybug in parts of Africa and Asia).

## 1.4 Augmentative biocontrol

### 1.4.1. Definition and description

When naturally occurring populations of beneficial organisms are insufficient to reduce pests, they can be augmented with releases of commercially reared natural enemies. In augmentative biological control, natural enemies of pests or antagonists of pathogens are mass-reared under controlled conditions and released with the aim of temporarily suppressing arthropod pests and diseases (Heimpel and Mills, 2017). There are two types of augmentative releases: inoculative releases and inundative releases. In inoculative releases, relatively few natural enemies are released, usually just once or twice at the start of the season to "inoculate" the cropping system. The introduced predators, parasitoids or microorganisms reproduce, and it is mainly their progeny (rather than the released individuals themselves) that provide biological control. In the case of inundative releases, large numbers of natural enemies are released, often repeatedly, over a growing season. Although they may reproduce, it is the released natural enemies that are relied upon to provide biological control in the short term.

### 1.4.2. Species used, production systems where used and examples of successes and failures

#### Species used

While the range of natural enemy species existing in nature is huge, only a limited number of species are used in augmentative biocontrol. These natural enemies may or may not be native to the area of release (Cock *et al.*, 2009; De Clercq, Mason and Babendreier, 2011). Van Lenteren *et al.* (2018) list more than 200 species used in augmentative biological control, but the majority of these are specialist natural enemies used against individual pest species, often on a limited scale. Other species have a wider host range and can be used more broadly. These include generalist predatory mites, predatory bugs and the egg-parasitoid genus *Trichogramma*, which is used over large areas in Brazil, Europe and China to control lepidopteran pests in cereals, cotton and other field crops (van Lenteren *et al.*, 2018).

A number of arthropod natural enemies have proven particularly successful and have become cornerstones of augmentative biological control. These include parasitic wasps such as *Trichogramma* spp., *Encarsia formosa*, and *Aphidius* spp., predatory mites such as *Phytoseiulus persimilis* and *Amblyseius swirskii*, predatory bugs such as *Macrolophus* spp. and *Orius* spp., lacewings, coccinellids and gall midges. Augmentative biological control with invertebrate natural enemies (so-called "macrobials") is extensively used in protected crops.[5] Riudavets and Vila (2020) provide a list of the most important invertebrate BCAs released in protected cultivation. The list comprises the following types of BCA: insect parasitoids, which often include generalist egg and pupal parasitoids, whereas larval parasitoids tend to be predominantly specialists, i.e. specific to a certain species or genus; generalist predatory mites preying on pest mites and small insects such as whiteflies and thrips; generalist insect predators, which can control a wide range of pests but which tend to have certain prey preferences; and entomopathogenic nematodes, which tend to be used against a range of soil-dwelling pests/pest stages. While the list has been extended over the years, species that were already used more than 50 years ago, such as the parasitic wasps *Encarsia formosa* and *Trichogramma* spp. and the specialist predatory mite *Phytoseiulus persimilis*, are still among the most important arthropod BCAs worldwide (De Clercq, Mason and Babendreier, 2011).

While augmentative biological control initially focused on specialist natural enemies, these have subsequently been complemented by more generalist BCAs, such as predatory bugs and generalist predatory mites (Janssen and Sabelis, 2015). These generalist predators not only feed on a wide range of prey but also exploit non-prey food such as pollen or fungi and supplemental factitious prey (Messelink *et al.*, 2014; Pijnakker *et al.*, 2020). This has made it possible to establish and maintain populations of generalist natural enemies in crops before the appearance of the target pest.

A range of microbial species are used for biological control (van Lenteren *et al.*, 2018). Viruses are mainly used to control lepidopteran pests (e.g. codling moth) and these tend to be highly specific. Various species of bacteria are in use both for pest and disease control, and many are formulated as biopesticides. *Bacillus thuringiensis* (Bt) is an example of a bacterium with different strains acting against different insect orders. The most commonly used strain is effective against caterpillar pests (Lepidoptera), while other strains act specifically against Diptera and Coleoptera. Other *Bacillus* spp., such as *B. amyloliquefaciens* and *B. subtilis*, can be used to control fungal diseases. As Bt products do not feature the living bacterium but rather the parasporal bodies formulated as a biopesticide, Bt does not fall under the stricter American definition of a BCA (Heimpel and Mills, 2017; Stenberg *et al.*,

[5] Crops protected by greenhouses, polytunnels or other artificial structures.

2021). The living spores of fungi such as *Lecanicillium muscarium*, *Metarhizium anisopliae* s.l. and *Beauveria bassiana* are used to control a wide range of pests, including whiteflies, thrips, aphids and even termites and locusts. Other fungi are antagonists that can be used against fungal problems such as *Trichoderma* spp., damping off and *Sclerotinia* spp.

### Production systems where used

Augmentative biological control is widely implemented in protected crops as part of integrated pest management systems, especially in tomato, sweet pepper and cucumber, but it is also increasingly used in protected ornamental crops, as well as in fruit crops and vineyards. A survey in the Netherlands showed that in 2016 biological control was used on 96 percent of the total surface area of greenhouse-grown vegetables and on 69 percent of greenhouse grown ornamentals, especially rose, chrysanthemum and gerbera (Statline, 2018). A similar survey in Canada showed that 92 percent of greenhouse ornamental growers were using biological control, in most cases as their main strategy (Summerfield, 2019). Biological control is also widely used in the production of berries, especially strawberries, both in protected crop systems in northern Europe and in open fields in other parts of the world, including Chile, Portugal, Spain and California.

Augmentative biological control is also used in certain large-scale field crops such as maize, other cereals, sugar cane and cotton. Van Lenteren *et al.* (2018) provide figures on the millions of hectares in the former Soviet Union, China, Mexico and South America where parasitoids are used to control lepidopteran pests. Recent data about augmentative biological control in Latin America and the Caribbean show that it is used in at least 27 countries on more than 31 million hectares of crops including as citrus, coffee, maize, cotton, soybean, sugar cane, mate, potato and quinoa (van Lenteren and Cock, 2020).

Augmentative biocontrol is increasingly used also in livestock production. Both parasitoids and predatory flies are used to control house flies and stable flies in dairy farms, and in horse and pig housing (Geden and Moon, 2009; Kaufman *et al.*, 2012). The immature stages of these flies develop in manure and the flies are a nuisance to the livestock. Predatory mites are used in poultry production to control chicken red mites, *Dermanyssus gallinae* (Lesna *et al.*, 2009; Zriki, Blatrix and Roy, 2020).

## 1.4.3. Benefits and risks

### Risks

Unlike in classical biological control, many species that are used for augmentative biological control are native organisms used to control native and/or invasive pests. Overall, the ecological impact of releasing these organisms has proven to be minimal, short-term and comparable to the usual fluctuations in natural-enemy population dynamics that occur in nature (Lynch *et al.*, 2001; van Lenteren *et al.*, 2006). If anything, it helps re-establish the balance between (crop) plants, pests and natural enemies when this is temporarily disturbed during pest or pathogen outbreaks (van Lenteren, Bueno and Klapwijk, 2021).

Pests, however, often do have an exotic origin, particularly in protected cultivation. Herbivorous species can become invasive when transported to new regions because these regions lack coevolved natural enemies. Cultivated crops can be especially vulnerable to invasive pests, as many of them are themselves not native to the area where they are produced. In certain cases, when native natural enemies are unable to control invasive pests, it may be necessary to consider introducing coevolved natural enemies that keep the pest in check in its region of origin. In addition to their introduction in classical biocontrol programmes (Section 1.3), such organisms can also be valuable tools in augmentative biocontrol. When crops are produced in a protected environment, such as a greenhouse, this usually entails climatic conditions different from those in the outside environment. This may require the use of species adapted to the conditions within the greenhouse. As long as the species are not able to survive the climate outside, the ecological risk is considered to be low (van Lenteren *et al.*, 2006; EPPO, 2014).

Although a substantial number of augmentative biological control species have in the past been used outside their natural range, this has rarely resulted in negative environmental effects (van Lenteren *et al.*, 2006; De Clercq, Mason and Babendreier, 2011; Palevsky, Gerson and Zhang, 2012). The decline of native ladybird beetle species following the introduction of the exotic ladybirds *Coccinella septempunctata* (in North America) and *Harmonia axyridis* (in North and South America, Europe and Africa) for the control of aphids in the 1980s and 1990s has been an exception (Rondoni *et al.*, 2020). These cases raised awareness that an environmental risk assessment is necessary before decisions are taken on the release of exotic natural enemy species in a new area (van Lenteren *et al.*, 2006; De Clercq, Mason and Babendreier, *et al.*, 2011; Rondoni *et al.*, 2020).

The need for regulation of the import and release of exotic invertebrate BCAs at an international level led to the development of the International Standard for Phytosanitary Measures 3, *Guidelines for the export, shipment, import and release of biological control agents and other beneficial organisms*, by FAO/IPPC (FAO, 2017). Over the past decades, scientists and regulators, together with industry, have developed guidelines and methods for risk assessment (Bigler, Babendreier and Kuhlmann, 2006; Paula *et al.*, 2020; van Lenteren *et al.*, 2006; Ehlers, ed, 2011). For instance, the European and Mediterranean Plant Protection Organization (EPPO), in collaboration with the International Organisation for Biological Control (IOBC), has published various standards for the safe use of invertebrate BCAs (EPPO Standards on Phytosanitary Measures 6/1–4). Unfortunately, these recommendations have not always been adhered to by authorities, and sometimes the risk assessment and registration requirements are not appropriate or not proportionate to the expected risks. This considerably slows the development of (cost-)effective biological control solutions and contributes to continued reliance on chemical pesticides.

### Benefits and drivers of use

A number of drivers have contributed to the remarkable growth of augmentative biological control:

*Economics.* The early adopters of augmentative biological control in North America and northern Europe were swayed by its cost-effectiveness. The inoculative introduction of the parasitic wasp *Encarsia formosa* at the beginning of the crop cycle, along with occasional releases of the spider mite predator *Phytoseiulus persimilis*, proved to be an effective alternative to labour-intensive weekly insecticide applications in tomato crops.

*Pesticide resistance.* The widespread use of synthetic fungicides and broad-spectrum insecticides from the 1950s onwards resulted in problems with pesticide resistance. This was aggravated by the elimination of natural enemies as a result of increasingly intensive pesticide regimes. An early example of this was pesticide resistance in the red spider mite (*Panonychus ulmi*) in apples, which was resolved via the introduction of an integrated pest management (IPM) programme involving releases of its predator *Typhlodromus pyri*. More recent examples include greenhouse pests, such as spider mites, developing resistance to 96 active ingredients, as well as pesticide resistance in the western flower thrips and the green peach aphid (Arthropod Pesticide Resistance Database, 2022). One of the important benefits of biological control is that pests generally do not develop resistance to their (invertebrate) natural enemies.

*Food safety.* Pesticide resistance and the resulting increase in pesticide use may result in crop products exceeding maximum residue levels. An example of this was seen in the case of the residue problem uncovered by Greenpeace in 2006 in vegetables produced in Almería, Spain (van Lenteren *et al.*, 2018). After this case came to light, supermarkets reacted by introducing and enforcing strict residue rules (far stricter than the legal standards). Within one year, production in Almería changed from being largely based on chemical pesticides to being largely based on augmentative biological control (van der Blom, 2010; van Lenteren *et al.*, 2018). Increasingly, cooperatives, auctions and supermarkets require growers/suppliers to produce their crops according to strict guidelines and standards, including in some cases requiring zero detectable residues in the final product. The certification of produce is increasingly done by the supply chain rather than by government organizations (Möhring and Finger, 2022; Hatanaka, Bain and Busch, 2005).

*Reduced availability of pesticides.* The number of pesticides available has decreased substantially over the last decade because of stricter regulation of pesticides with high environmental risk. For example, the effects of neonicotinoids on pollinators resulted in a ban in Europe (Butler, 2018).

## 1.4.4. Extent of adoption, economic value and differences between regions

Commercial augmentative biological control has been around for almost 100 years and has proven to be a viable alternative to the use of chemical pest control, especially in protected crops, but also in an increasing range of arable cropping systems. Augmentative biological control has made remarkable progress since the parasitic wasp *Encarsia formosa* was first used in 1926 to control whitefly in California and the United Kingdom (Speyer, 1927). From the 1960s, augmentative biological control grew from a niche activity into a professional and commercially successful venture. This success was supported by years of fundamental and applied research, and considerable investments by the private sector. There are about 500 commercial producers of augmentative BCAs worldwide (van Lenteren *et al.*, 2018). The majority of these are small- to medium-sized companies, with a handful of larger, globally acting players. The last decade has seen consolidation by the larger biological control companies through mergers and acquisitions (van Lenteren *et al.*, 2018). In parallel, large agrochemical companies have acquired manufacturers of microbial biopesticides, semiochemicals and natural products (van Lenteren *et al.*, 2018).

From the limited number of products available in the 1960s, augmentative biological control now provides full portfolios for crop protection, including macrobial and microbial products. Over the last decade, the market growth for biological control has outperformed the growth of chemical pesticide products (van Lenteren *et al.*, 2018). Augmentative biological control is by now the main crop protection strategy in a number of protected crops. The widespread use of natural enemies in certain open-field crops, namely citrus, coffee, maize, cotton, soybean and sugar cane, shows that augmentative biological control can also be effective and competitive in arable farming.

### Economic value

The International Biocontrol Manufacturers Association (IBMA) estimated that between 2014 and 2018 there was a global annual increase of more than 20 percent in the total sales of macrobial and microbial BCAs combined (IBMA, 2020).[6] The period from 2016 to 2018 saw sales of invertebrate BCAs increase by 50 percent, while sales of microbials and semiochemicals almost doubled (figures based on the 38 percent of the industry sampled by IBMA). In 2018, the European biological control market was EUR 1.015 (USD 1.161) billion, representing approximately 6 percent of the EUR 16 (USD 18.3) billion crop-protection market.[7] Half of these sales were represented by actual biological organisms (macrobials and microbials), with macrobials having a slightly higher market share than microbials. The remainder were made up of semiochemicals and natural substances. Globally, microorganisms represent a larger share of the biological control market than macrobials.

### Differences between regions

Out of the USD 4.121 billion biocontrol sales worldwide (including semiochemicals and natural substances), the North American market is the largest at USD 1.26 billion, followed by Europe (USD 1.14 billion), South America (USD 0.69 billion) and Asia–Pacific (USD 0.46 billion) (IBMA, 2020).[8] Europe remains the largest market in terms of natural-enemy sales, with more than USD 286 million sales in 2018, followed by the Americas. The Americas lead in terms of microbial biopesticides, with sales worth more than USD 343 million.

### Differences between developed and developing countries

In developed countries, the primary use of biocontrol remains in protected crops (vegetables, fruits and ornamentals). The role of augmentative biological control in open-field crops is growing, with successful examples in vineyards and horticulture, as well as in arable crops (maize). Augmentative biological control is also increasingly used in public green spaces and indoor landscaping, often combined with conservation biological control practices.

In developing countries, the main success stories are the use of augmentative biological control in citrus, coffee, maize, cotton, soybean and sugar cane. Augmentative biological control is also widely used in fruits, vegetables and ornamentals, but mainly when these are produced for the European and American markets. There are, however, examples of biological control solutions especially developed for use by smallholder farmers. A nice example is the "Toothpick Project", in which smallholder farmers are provided with toothpicks with an inoculum of a specific strain of the fungus *Fusarium oxysporum* that can be reproduced on farm and used to control witchweed (*Striga hermonthica*), which is a severe threat to the production of maize and other staple crops in sub-Saharan Africa (Nzioki *et al.*, 2016).

## 1.4.5. Needs and challenges for further adoption

Because of increased interest in biological control, including in open-field markets, there is a growing need for indigenous natural enemies that are well adapted to local climatic conditions. However, for the control of exotic pests, exotic natural enemies may also be needed, especially in protected crops. ABS under the Nagoya Protocol (Section 4.5) is therefore a consideration and a challenge. Although best practices have been developed (Mason *et al.*, 2018), and in many cases the use of BCAs is not within scope of the regulations, lack of experience in dealing with ABS issues is seriously slowing the access process.

[6] All figures presented in this paragraph are based on IBMA (2020).
[7] Conversion to USD based on 2018 exchange rates.
[8] All figures presented in this paragraph are based on IBMA (2020).

An important factor affecting the adoption of augmentative biological control is regulation of the use of biological control products. The International Standard for Phytosanitary Measures (ISPM 3) developed by FAO/IPPC was meant to provide the framework for further regulation at national level. Developments at national level have, however, resulted in a wide variety of regulations, some of which are not appropriate for invertebrate BCAs (Barratt *et al.*, 2021). It is still often the case that national regulators have expertise in pesticide registration and are not familiar with the specific nature and characteristics of biological control. In some countries, specific supportive regulations have been developed, but in other countries disproportional or inappropriate requirements and lengthy procedures are seriously hampering the registration and uptake of biological control. To make safe and effective biological crop protection solutions available to farmers, there is a need for appropriate, balanced regulation and for regulators that have a background in biology and biological control. In a country such as Colombia, one of the major flower-producing countries in the world, growers need biological control products because of pesticide resistance problems but do not have access to them, as local production is insufficient and import is impossible because of unrealistic regulations (Kondo, Manzano and Cotes, 2020). In Europe, strict, and sometimes disproportionate, national or regional regulations are delaying or preventing biological control options from reaching the market. Recently the Portuguese presidency of the European Union (EU) launched a discussion on the potential benefits of greater harmonization of Member States' legislation on BCAs. EU Council Decision 9520/21 requested "the [European] Commission to submit a study on the [EU's] situation and options regarding the introduction, evaluation, production, marketing and use of biological control agents within the territory of the [EU] and a proposal, if appropriate in view of the outcomes of the study."[9]

A serious additional threat to augmentative biological control is that a few countries have recently started to enforce their political borders, rather than species' (natural) ecological ranges, in the registration process of BCAs. By requiring the production of "national strains" they ignore the fact that naturally occurring BCAs are not held by political borders and often migrate over hundreds or thousands of kilometres (Wotton *et al.*, 2019). They interbreed across their extended ecological ranges, which typically cover many countries. The requirement to produce national strains ignores this ecological reality and generates no ecological benefits. The resulting fragmentation of biological control production adds substantially to the costs of augmentative biological control (raising end-user prices two to fourfold), which favours the use of chemical pesticides, with their well-established adverse ecological and health impacts.

Augmentative biological control is not a stand-alone solution. For good results, it has to be embedded in sustainable production systems built on supportive agricultural landscapes. Incorporating landscape features that provide BCAs with resources such as food, shelter and overwintering sites supports the supply of pest control ecosystem services (Ramsden *et al.*, 2015; Gurr *et al.*, 2017). The sustainability of the production system can also be improved through practices such as crop rotation and appropriate soil management that support the production of healthy plants. Plant breeding to develop crop varieties that are less susceptible to pests and diseases also plays an important role. Crop varieties could also be selected to support BCAs, for instance by providing extrafloral nectar as food or hairs as shelter. Natural enemies should be considered when developing pest-monitoring systems and damage thresholds. Current damage thresholds tend to be based on the monitoring of pests and pathogens only. By recording levels of both pests and their natural enemies, thresholds can be adapted and unnecessary interventions avoided.

[9] https://www.consilium.europa.eu/en/meetings/agrifish/2021/06/28-29/

# Chapter 2. Status and trends of biological control agents

This chapter provides an overview of the diversity of the microorganisms and invertebrates that provide biological control services and considers the status and trends of this diversity and the threats affecting it.

## 2.1. Microorganisms

### 2.1.1. The diversity of microbial biological control agent species and subspecies

Microbial BCAs include viruses, bacteria, fungi and protozoa that infect and debilitate or kill invertebrate pests, weedy plants or other microorganisms, and microorganisms that displace pathogens by competition for surfaces or nutrients or by antagonistic processes such as the production of toxic substances (Waage, 2007).

Little is known about microorganisms in general: it is estimated that 99 percent still remain to be discovered (Locey and Lennon, 2016; Smith *et al.*, 2018). There are various estimates of the numbers of microorganisms on Earth. These include estimates of up to 3.8 million species of fungi (Hawksworth and Lücking, 2017), up to 5.1 million species of fungi (Blackwell, 2011) and up to 1 million species of prokaryotes (Louca *et al.*, 2019). The number of microbial BCAs occurring in nature is unknown. Microorganisms, however, are increasingly used as BCAs, as illustrated by a significant increase over time in the total global area on which they are applied (up from a few thousand hectares in 1970 to approximately 20 million hectares in 2018), and the increasing number of species used as commercial microbial BCAs (five in 1970 and 94 in 2018) (van Lenteren *et al.*, 2018, 2020; van Lenteren, Bueno and Klapwijk, 2021).

One hundred and thirty-one species of fungi, viruses and nematodes have been used for biological control of arthropods (Hajek, McManus and Delalibera, 2007). Thirty fungal species have been used as biological control agents against weeds (Schwarzländer *et al.*, 2018). Two hundred and nine microbial species/strains have been used in augmentative biological control (van Lenteren *et al.*, 2018). Approximately 38 microbial species/strains have been used for biological control of plant pathogens (O'Brien, 2017).

Van Lenteren *et al.* (2018) present a list of 94 strains of bacteria, representing 28 species, and over 80 strains of fungi, representing 39 species, reported as having been registered for use as plant protection products. Other sources include the list of pathogens used as BCAs given in *Classical biological control of insects and mites: a worldwide catalogue of pathogen and nematode introductions* (Hajek, Gardescu and Delalibera, 2016). However, again this list is far from exhaustive and includes only a single bacterium and 18 species of fungi. Attempts have been made to collate and present data on a global basis, including through the Bioprotection Portal (see below).

#### Literature survey

Analysis of published works and the numbers of strains that are available from producers and public collections can give an indication of the extent to which the strains mentioned in published works are available for use. A search of the 13 944 000 records held in CAB Direct (https://www.cabdirect.org/), considered to be the most thorough and extensive source of reference in the applied life sciences,[10] revealed 146 630 records containing the term "biocontrol" and 108 511 containing the term "biocontrol agents". Limiting the search to literature specifically mentioning the use of the term "biological control agents" gave 39 279 hits. Additionally, there are natural enemy tables in around 2000 pest and invasive species datasheets that include microorganisms as well as invertebrates, but it is difficult to know whether species have been actively used as BCAs until the records have been extracted and analysed. With considerable investment of time, a list of microorganisms used as natural enemies of pests and invasive species could be created.

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[10] Various other literature sources are available, for example ResearchGate https://www.researchgate.net/, Web of Science https://www.webofknowledge.com and Google Scholar https://scholar.google.com). A wider review would be necessary in order to get full coverage.

Analysis of data within CABI's BioProtection Portal,[11] a free, web-based tool that provides information on registered biological control products (microorganisms, invertebrate BCAs, natural substances and semiochemicals), showed that across 15 countries (Bangladesh, Brazil, Canada, Chile, Colombia, France, Ghana, Hungary, Kenya, Morocco, Peru, Portugal, Spain, Uganda and the United Kingdom) there were some 1 004 microbial BCA plant-protection products registered, representing almost a third of the total BCA products for these countries (Table 1). The 1 004 microbial products consisted of 97 different microbial species or combinations of species (45 fungi, 31 viruses and 21 bacteria) and were authorized for use against a wide range of pests and diseases of various crops, both outdoor and protected.

The Bioprotection Portal has some way to go to cover all countries, but it has made a good start and demonstrates the value of bringing this information together. The figures for the 15 countries included so far show larger numbers of registered products than listed in the publications cited above (e.g. van Lenteren *et al.* 2018; Hajek *et al.*, 2016), with over 1 000 products utilizing over 950 different isolates of BCAs in the 38 genera of bacteria and fungi listed in Table 1, in addition to a further 86 virus products. There will be products registered for use in more than one country.

**Table 1. Microbial and invertebrate biological control agents from the 15 countries covered by the Bioprotection Portal**

| Region | Country | Product total | Products by category | Representative genera |
|---|---|---|---|---|
| Africa | Ghana | 11 | Bacteria 6 | *Bacillus* |
| | | | Fungi 4 | *Beauveria, Metarhizium, Aspergillus, Trichoderma* |
| | | | Virus 1 | |
| | Kenya | 37 | Bacteria 12 | *Bacillus, Pseudomonas* |
| | | | Fungi 24 | *Ampelomyces, Aspergillus, Beauveria, Trichoderma, Lecanicillium, Metarhizium, Myrothecium, Isaria, Purpureocillium* |
| | | | Virus 1 | |
| | Morocco | 34 | Bacteria 20 | *Bacillus* |
| | | | Fungi 9 | *Ampelomyces, Ampelomyces, Beauveria, Gliocladium, Isaria, Purpureocillium, Pythium, Trichoderma* |
| | | | Virus 5 | |
| | Uganda | 17 | Bacteria 3 | *Bacillus, Pseudomonas* |
| | | | Fungi 12 | *Beauveria, Metarhizium, Trichoderma, Lecanicillium, Verticillium* |
| | | | Fungi + Bacteria 1 | *Trichoderma, Metarhizium, Bacillus* |
| | | | Virus 1 | |

[11] www.bioprotectionportal.com

| Region | Country | Product total | Products by category | Representative genera |
|---|---|---|---|---|
| Asia | Bangladesh | 5 | **Bacteria 1** | *Pseudomonas* |
| | | | **Fungi 1** | *Trichoderma* |
| | | | **Fungi + Bacteria 1** | *Trichoderma, Streptomyces, Geobacillus* |
| | | | **Virus 2** | |
| Europe | France | 87 | **Bacteria 37** | *Bacillus, Pseudomonas, Streptomyces* |
| | | | **Fungi 35** | *Beauveria, Trichoderma, Phlebiopsis, Candida, Gliocladium, Ampelomyces, Aureobasidium, Lecanicillium, Clonostachys, Coniothyrium, Phlebiopsis, Purpureocillium, Pythium* |
| | | | **Virus 11** | |
| | | | **Yeast 4** | *Metschnikowia, Saccharomyces* |
| | Hungary | 11 | **Bacteria 2** | *Bacillus* |
| | | | **Fungi 9** | *Beauveria, Pythium, Trichoderma, Aureobasidium* |
| | Portugal | 44 | **Bacteria 20** | *Bacillus, Pseudomonas* |
| | | | **Fungi 18** | *Aureobasidium, Beauveria, Coniothyrium, Isaria, Lecanicillium, Purpureocillium, Pythium, Trichoderma* |
| | | | **Virus 6** | |
| | Spain | 76 | **Bacteria 44** | *Bacillus, Pseudomonas* |
| | | | **Fungi 24** | *Beauveria, Metarhizium, Trichoderma, Pythium, Coniothyrium, Aureobasidium, Isaria, Lecanicillium, Purpureocillium* |
| | | | **Virus 8** | |
| | United Kingdom | 37 | **Bacteria 14** | *Bacillus, Pseudomonas* |
| | | | **Fungi 14** | *Beauveria, Trichoderma, Verticillium, Phlebiopsis, Candida, Gliocladium, Ampelomyces, Aureobasidium, Lecanicillium, Phlebiopsis* |
| | | | **Virus 9** | |

| Region | Country | Product total | Products by category | Representative genera |
|---|---|---|---|---|
| Latin America | Brazil | 223 | Bacteria 73 | *Bacillus, Pasteuria* |
| | | | Fungi 123 | *Beauveria, Metarhizium, Hirsutella, Isaria, Purpureocillium, Pochonia, Trichoderma* |
| | | | Fungi + Bacteria 2 | *Trichoderma, Bacillus* |
| | | | Virus 25 | |
| | Chile | 59 | Bacteria 17 | *Bacillus, Agrobacterium* |
| | | | Fungi 39 | *Metarhizium, Trichoderma, Beauveria, Purpureocillium, Arthrobotrys* |
| | | | Fungi + Bacteria 1 | *Bionectria, Hypocrea, Bacillus* |
| | | | Virus 2 | |
| | Colombia | 117 | Bacteria 30 | *Bacillus, Burkholderia, Paenibacillus, Streptomyces* |
| | | | Fungi 83 | *Beauveria, Metarhizium, Trichoderma, Purpureocillium, Entomophthora, Pochonia* |
| | | | Fungi + Yeast 1 | *Beauveria, Purpureocillium, Trichoderma, Saccharomyces* |
| | | | Virus 3 | |
| | Peru | 121 | Bacteria 70 | *Bacillus, Pseudomonas* |
| | | | Fungi 50 | *Beauveria, Metarhizium, Trichoderma, Pythium, Hirsutella, Entomophthora, Isaria, Purpureocillium, Lecanicillium* |
| | | | Virus 1 | |
| North America | Canada | 125 | Bacteria 79 | *Bacillus, Agrobacterium, Pseudomonas, Pantoea, Clavibacter, Pasteuria, Streptomyces* |
| | | | Fungi 35 | *Beauveria, Metarhizium, Trichoderma, Aureobasidium, Chondrostereum, Coniothyrium, Gliocladium, Nosema, Phlebiopsis, Purpureocillium, Phoma, Sclerotinia, Verticillium* |
| | | | Virus 11 | |

*Source:* Data extracted from www.bioprotectionportal.com, accessed May 2021.

### 2.1.2. Status, trends and threats

Little is known about the status and trends of microorganisms in general or microbial BCAs in particular. It is generally considered that microbial diversity is under threat from habitat destruction and other drivers of biodiversity loss. Several fungi are known to be threatened with extinction. For example, the United Kingdom Red Data List of Threatened British Fungi[12] includes 400 endangered species. As of 2022, the International Union for Conservation of Nature (IUCN) Red List of Threatened Species[13] includes 550 fungal species, of which 28 are classed as critically endangered, 95 as endangered, 141 as vulnerable, 58 as near threatened, 180 as of least concern and 48 as data deficient. However, no information about whether these species are BCAs is provided.

## 2.2. Invertebrates

### 2.2.1. The diversity of species and subspecies

The following discussion is based on BCA species, as the status of subspecies is open to discussion and not recognized by many ecologists and taxonomists, for example most hymenopterists. It is possible that particular strains of a natural enemy adapted to an ecozone, crop or pest may prove useful, but this is not reflected in formal taxonomy. Furthermore, recent integrative taxonomic work incorporating molecular evidence has revealed that many populations hitherto treated as subspecies are valid species, and that some (perhaps many) generalist parasitoids comprise a complex of generalist and more or less host-specific species that are morphologically difficult or impossible to separate (e.g. Smith *et al.*, 2007, 2013). There is a significant taxonomic impediment to cataloguing potentially useful BCAs, especially in less-developed countries, and this needs to be addressed.

**Invertebrate predators** tend to be generalists in the type of prey they feed on, although there are also many that specialize in particular families, genera or species of prey. Generalist predators are often important in conservation biological control, particularly where populations can build up on non-pest species. They are used in augmentative biological control but need to be carefully selected and matched to the pest in field situations and are more likely to have significant impact on individual target pest species in enclosed environments such as greenhouses (including polytunnels and other plastic-covered growing structures). In recent years, non-native generalist predators have tended not to be recommended in classical biological control, because of the risk of unwanted non-target feeding and indirect impacts. However, recent thinking suggests that they may still have a role but that this needs to be based on an appropriate comprehensive environmental risk assessment (Andow *et al.*, 2021 and other papers in the special issue). Hence, there are significant regulatory impediments to introducing non-native predators. Specialist predators may be used in all types of biological control.

It is difficult to generalize about the most important groups of invertebrate predators for conservation biological control, but groups such as spiders, ants, predatory wasps, predatory beetles, predatory bugs and predatory mites are frequently highlighted. The families of invertebrate predators most commonly used in classical biological control are shown in Table 2. For the most used species, see Tables 1 and 4 in Cock *et al.* (2010).

Predators are the dominant BCAs used for augmentative biological control in greenhouses. The predatory mite species *Amblyseius swirskii*, *Phytoseiulus persimilis* and *Neoseiulus californicus* (Phytoseiidae) are by far the most frequently used invertebrate BCAs, and together account for more than 60 percent of the total turnover of commercially used BCAs (Klapwijk and Knapp, 2018). Predatory bugs in the families Anthocoridae and Miridae account for another 10 percent each. In contrast, parasitoids dominate in augmentative biological control in field crops.

**Invertebrate herbivore** BCAs are those species that feed on weeds. To date there is a negligible track record in their use in conservation biological control, maybe with the exception of seed feeders (Davis and Raghu, 2010; Sarabi, 2019; Blubaugh *et al.*, 2016), and only a few cases in which they have been used in an augmentative approach. However, they are widely used in the classical biological control of weeds. Many invertebrate herbivore species specialize in feeding on a family, genus or species of plant, often making them suitable for use as BCAs. There are significant regulatory hurdles to introducing non-native herbivores, but risk evaluation protocols and procedures for introduction are well established, at least in the regions where they are most used (Hunt *et al.*, 2008).

Below-ground herbivores have a higher chance of

[12] https://www.britmycolsoc.org.uk/field_mycology/conservation/red-data-list/rdl-taxa
[13] https://www.iucnredlist.org/

**Table 2. Main families of predators used in classical biological control (i.e. those that had been introduced at least 20 times up until 2010)**

| Family | Number of classical biological control introductions made up to 2010 |
|---|---|
| Coccinellidae | 951 |
| Histeridae | 93 |
| Carabidae | 82 |
| Anthocoridae | 21 |
| Reduviidae | 20 |

*Source*: Greathead, D.J. & Greathead, A.H. 1992. Biological control of insect pests by insect parasitoids and predators: the BIOCAT database. *Biocontrol News and Information*, 13: 61N–68N; Cock, M.J.W., Murphy, S.T., Kairo, M.T.K., Thompson, R., Murphy, R.J. & Francis, A.W. 2016. Trends in the classical biological control of insect pests by insects: an update of the BIOCAT database. *BioControl*, 61: 349–363.

**Table 3. Main families of invertebrates used in classical biological weed control**

| Family | Number of biocontrol agent species released up to 2020 |
|---|---|
| Chrysomelidae | 104 |
| Curculionidae | 80 |
| Tephritidae | 30 |
| Tortricidae | 20 |
| Brentidae | 18 |
| Crambidae | 17 |
| Cerambycidae | 17 |
| Eriophyidae | 16 |
| Cecidomyiidae | 15 |

*Source:* ibiocontrol. 2021. Biological Control A World Catalogue of Agents and their Target Weeds. Cited June 2021. https://www.ibiocontrol.org/catalog/

getting established than above-ground herbivores (77.5 percent vs 67.2 percent) and are more likely to contribute to control (53.7 percent vs 33.6 percent) (Blossey and Hunt-Joshi, 2003). BCAs with native "ecological analogues" (i.e. native insects that are taxonomically related to the BCA and have a similar lifestyle niches and feed on the target weed) have a greater risk of being attacked by parasitoids once released and consequently being less successful than BCAs without native analogues (Paynter *et al.*, 2010; Paynter, Fowler and Groenteman, 2018).

Three insect orders, Coleoptera, Lepidoptera and Diptera, comprise approximately 80 percent of all invertebrate BCAs released for the classical biological control of weeds (Schwarzländer *et al.*, 2018). Within the Coleoptera, the highest numbers of BCA species released are within the families Chrysomelidae and the Curculionidae (Table 3).

**Invertebrate parasitoid** BCAs are those species that live in close association with their host at the host's expense, eventually resulting in the death of the host. They are important in all types of biological control. The families of invertebrate parasitoids most commonly used in classical and augmentative biological control are shown in Tables 3 and 4; all the commonly used families are in the order Hymenoptera, apart from the Tachinidae (Diptera). Among the parasitoids, the Chalcidoidea are the most successful in classical biological control, particularly members of the families Aphelinidae and Encyrtidae (Van Driesche, Cock and Winston, forthcoming).

Compared to predators, parasitoids are relatively little used in commercial greenhouse augmentative control today (Section 1.4). In protected crops, the most commonly used parasitic wasps are those in the family Chalcidoidea (*Encarsia formosa, Eretmocerus eremicus*), which together account for 12 percent of the turnover of commercially used BCAs. In contrast, *Trichogramma* spp. (Trichogrammatidae), dominate in augmentative biological control of pests of field crops as egg parasitoids of Lepidoptera pests.

**Natural and conservation biological control.** Invertebrate species important in these types of biological control are limited to those already naturally present in the ecosystem. Although the providers of natural and conservation biological control include all types of natural enemies, including microorganisms, nematodes and vertebrates such as insectivorous birds and bats, invertebrates are among the most significant contributors. The interactions between different pests, between pests and their natural enemies and between different natural enemies are complex. Careful, detailed study is needed to tease out the key BCAs involved in the control of a particular pest. Establishing mortality factors and devising and validating mechanisms to manipulate them to minimize pest damage is challenging, time-consuming, expensive and likely to be specific to a region or ecozone. Hence it is difficult to specify which groups of natural enemies are critical for a given pest in a given crop in a given area in a given season. A more pragmatic approach has been to encourage the presence of many groups of natural enemies in target areas.

However, there are cases in which specific mechanisms underlying natural biological control are understood. For instance, *Nilaparvata lugens*, the rice brown planthopper (BPH) is typically controlled by spiders (Araneidae, Linyphiidae, Lycosidae, Tetragnathidae) when it moves into a recently planted rice paddy. This depends on an adequate population of generalist predatory spiders being present when the BPH arrives, and this in turn depends on the presence of alternative food sources. The food sources in question have been shown to be small flies breeding in the mud of the rice paddy, which boost spider numbers at the beginning of the rice crop cycle (Radermacher *et al.*, 2020). There are also some well-known examples of management practices that benefit specific biological control mechanisms, such as the use of grass strips in cereal crops in Europe for the control of aphids by carabids (Collins *et al.*, 2002; Holland *et al.*, 2020) and the use of alyssum in lettuce for the control of aphids by syrphid flies (Brennan, 2013).

**Classical (importation, introduction) biological control** is used almost exclusively against invertebrates (predominantly insects) and weeds (see Section 1.3). The types of BCAs used for classical biological control of these two groups are completely different and are treated separately here.

BCAs used for classical biological control of invertebrate pests are either parasitoids or predators. Classical biological control has been practised against insect pests for more than a century. At least 2 384 species of 740 genera, from 85 families, 55 superfamilies and 10 orders have been used. The breakdown by the most-used families is shown in Table 4. The practice of classical biological control has changed over time as societal values have changed (Heimpel and Cock, 2018). There has been a shift towards more host-specific natural enemies that are less likely to have adverse effects on beneficial species, and recently the focus has been on BCAs that present minimal risk to any indigenous species. Because many groups of parasitoids are relatively host-specific and many predators are more generalist, this has led to a shift in emphasis towards parasitoids and away from predators (Figure 2). Nevertheless, specialist coccinellid predators continue to be used and useful (Rondoni *et al.*, 2020).

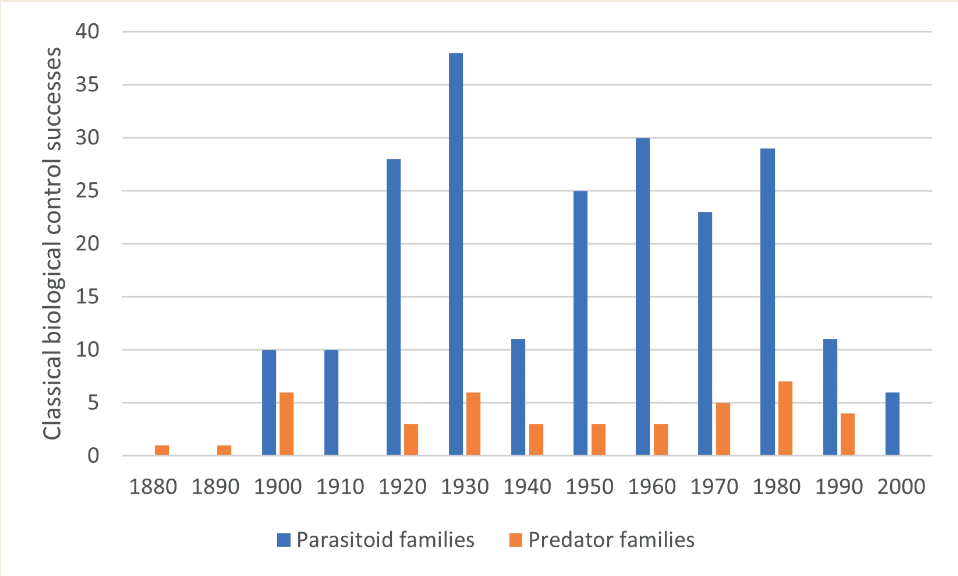
**Table 4. Main families of parasitoids used in classical biological control**

| Family | Number of classical biological control introductions made up to 2010 |
|---|---|
| Braconidae | 1136 |
| Aphelinidae | 713 |
| Encyrtidae | 662 |
| Ichneumonidae | 487 |
| Eulophidae | 390 |
| Tachinidae | 388 |
| Pteromalidae | 189 |
| Platygastridae | 180 |
| Trichogrammatidae | 180 |
| Scoliidae | 81 |
| Chalcididae | 52 |

*Note*: Figures shown for families introduced at least 50 times up to 2010.
*Source*: Greathead, D.J. & Greathead, A.H. 1992. Biological control of insect pests by insect parasitoids and predators: the BIOCAT database. *Biocontrol News and Information*, 13: 61N–68N; Cock, M.J.W., Murphy, S.T., Kairo, M.T.K., Thompson, R., Murphy, R.J. & Francis, A.W. 2016. Trends in the classical biological control of insect pests by insects: an update of the BIOCAT database. *BioControl*, 61: 349–363.

BCAs used for classical biological control of weeds are normally insect herbivores or plant-pathogenic fungi (Section 2.1). In contrast to insect biological control, weed biological control has focused much more on relatively host-specific BCAs from the beginning, so there has not been such a noticeable shift in the guilds of BCAs used. Table 3 shows the most frequently used families of weed BCAs. However, in principle any herbivore that shows suitable host-specificity and attacks the target weed in such a way as to cause significant

**Figure 2. Number of first substantial classical biological control successes per decade achieved by all parasitoid families versus all predator families**




*Source*: Greathead, D.J. & Greathead, A.H. 1992. Biological control of insect pests by insect parasitoids and predators: the BIOCAT database. *Biocontrol News and Information*, 13: 61N–68N; Cock, M.J.W., Murphy, S.T., Kairo, M.T.K., Thompson, R., Murphy, R.J. & Francis, A.W. 2016. Trends in the classical biological control of insect pests by insects: an update of the BIOCAT database. *BioControl*, 61: 349–363.

damage (reducing vigour and seed production) could be considered. Hemiptera, Coleoptera and fungal pathogens are the BCA groups with the highest proportions of species that have been found to cause complete to substantial control (Schwarzländer *et al.*, 2018).

**Augmentative biological control**. In the past, augmentative biological control has used both indigenous and introduced BCAs, but there has been a trend in recent years to focus on indigenous natural enemies that are adapted to feeding on or parasitizing the target pest – whether the pest is indigenous or introduced in the region (Figure 1 in Cock *et al.*, 2010). Safety and access issues have been major drivers in this shift. In order for a BCA to be used for augmentative biological control, it needs to be amenable to mass-production (often based on newly developed techniques), be suitable for transport from the production facility to where it is needed (e.g. as parasitized eggs or in the egg or pupal stage) and be adapted to the target crop ecosystem, where it will remain while food supplies last. Such BCAs can be parasitoids or predators, and both are used, although predators dominate.

A relatively small number of invertebrate species (25) are currently used for biological control in greenhouses, and many of these are used worldwide (van Lenteren, 2012; Klapwijk and Knapp, 2018; Section 1.4). This is because the same crops are grown in greenhouses worldwide, similar environments are created in greenhouses and the same pests occur all over the world (specifically, a few species of thrips, spider mite and whitefly that are polyphagous and able to adapt to different climates).

It is also the case that relatively small numbers of invertebrate BCAs are used in field crops, and these are almost all parasitoids. For example, in Latin America, egg-parasitic *Trichogramma* spp. wasps are used against Lepidoptera pests on various crops covering about 2.7 million hectares, Braconidae larval-parasitoids are used against sugar-cane borers (Crambidae) on 0.4 million hectares and against pine shoot moth (Tortricidae) on 50 000 hectares, and egg parasitoids are used against soybean stink bugs (Pentatomidae) on 30 000 hectares (van Lenteren *et al.*, 2020). *Trichogramma* spp. are also widely used against Lepidoptera pests of various crops in Asia, especially China (5 million hectares) and the former Soviet Union (10 million hectares, but no recent data available), Southeast Asia (300 000 hectares), Northeast Africa (300 000 hectares) and Europe (50 000 hectares) (van Lenteren *et al.*, 2018).

In weed biological control, there are some examples in which native invertebrate species are being used in an augmentative approach to control native weed species. For instance, augmentative releases of the fly *Phytomyza orobanchia* can provide good control of parasitic weeds in the family Orobanchaceae (Winston *et al.*, 2014).

### 2.2.2. Status, trends and threats

Species and particular strains or biotypes of BCAs are going extinct locally, regionally and probably globally. However, there is no effective documentation of this process except at small scales. Proving extinction of a BCA is not straightforward, and there is no investment in attempting to do this. Maintaining healthy biodiverse agroecosystems, especially organic ones, will minimize this risk.

**Natural and conservation biological control** depends on the presence in the crop ecosystem of natural enemies that can reduce pest populations to an acceptable level. The species of BCA present and their population levels depend on multiple factors. However, the intensification of agriculture, with larger fields, reduced margins, elimination of weeds, intensive soil preparation and the use of various chemical insecticides has negative effects on the diversity and population levels of natural enemies (Brooks *et al.*, 2012; Hallmann *et al.*, 2017; Lichtenberg *et al.*, 2017; Liere, Jha and Philpott, 2017; Redhead *et al.*, 2020), posing risks to the long-term presence of natural enemies. Their elimination leaves crops open to pests that are adapted to intensive agriculture and mobile enough to colonize them.

The establishment of refuge areas such as flower strips can reduce the risk of loss and lead to the recovery of natural-enemy populations (Holland *et al.*, 2016). In the absence of such areas, it is possible that many natural enemies are being eliminated from large areas of intensive agriculture. Species, and especially locally adapted strains, of natural enemies are likely to become locally or globally extinct. Climate change is expected to exacerbate this trend, especially for less mobile natural enemies (Sánchez-Bayo and Wyckhuys, 2019).

**Classical biological control** depends on the ability to go to the area of origin of a pest or weed and assess the indigenous natural enemies that typically keep it under control for their suitability and safety for introduction elsewhere. Some target species may be rare in their area of origin, and it follows that any host-specific BCAs will also be rare. It is certainly likely that land-use change, introduction of new crops and climate change are leading to the local extinction and potentially global extinction of BCA species, including BCAs whose potential value has never been considered. As yet, this has hardly been documented – the failure to find a target species in its supposed area of origin may be due to other factors – but it can be expected to happen in the future. Quite apart from the rarity of a target species in its area of origin, there may be significant difficulties in accessing natural enemies because of logistics (very remote areas), political instability or ABS regulations (or lack of them) (Cock *et al.*, 2010; Silvestri *et al.*, 2020; Section 4.5).

**Augmentative biological control**. For non-indigenous augmentative BCAs, the same concerns apply as for classical BCAs, including rarity, accessibility issues and regulatory issues. The search for indigenous natural enemies will be constrained by intensive agriculture as outlined above, and it is possible that special "safe plots" will need to be established in order to find out what potentially useful BCAs exist. Candidate indigenous natural enemies are often identified when they show up naturally during a pest outbreak in agricultural crops, either conventional or organic. This has the advantage that the species involved have already shown adaptation to cropping systems. In other instances, species are collected in organic agroecosystems or semi-natural ecosystems. Here "safe plots" designed for such collections would be effective, although local, regional or global extinction will make this increasingly less practical.

Individual strains of BCAs may be important, for example strains that show heat tolerance, have adapted to a target pest or are better able to develop on suboptimal food (e.g. Mendoza *et al.*, 2021 working on *Orius* spp.). However, these strains will change as they pass through a genetic bottleneck when taken into culture and production (Vorsino *et al.*, 2012; Francuski *et al.* 2014; Li *et al.*, 2015; Retamal *et al.*, 2016).

### 2.2.3. Regional differences

There are clear differences between regions in terms of how well BCA taxonomy is understood. In particular, the BCAs that occur naturally in developed countries are likely to be better known than those in less-developed countries. This is exacerbated by the tendency for the BCA fauna of tropical countries to be richer. In contrast, there is also a tendency for the relatively impoverished BCA fauna of isolated oceanic islands to be better known, at least with regard to the main crop pests.

**Natural and conservation biological control.** While many BCA species have an extensive geographical

**Table 5. Zoogeographical origins of insect microbial and invertebrate biological control agents used in classical biological control of insect pests**

| Zoogeographical region | Number of unambiguously sourced introductions for classical biological control of insects |
|---|---|
| West Palaearctic | 1108 |
| Neotropical | 766 |
| Nearctic | 706 |
| Afrotropical | 588 |
| Australasia | 545 |
| Malesian | 504 |
| Caribbean | 441 |
| Oriental | 375 |
| East Palaearctic | 301 |
| Pacific | 276 |
| Mascarene | 122 |

*Source*: Greathead, D.J. & Greathead, A.H. 1992. Biological control of insect pests by insect parasitoids and predators: the BIOCAT database. *Biocontrol News and Information*, 13: 61N–68N; Cock, M.J.W., Murphy, S.T., Kairo, M.T.K., Thompson, R., Murphy, R.J. & Francis, A.W. 2016. Trends in the classical biological control of insect pests by insects: an update of the BIOCAT database. *BioControl*, 61: 349–363. Figures based on only those records where the origin seems unambiguous.

range, there are assumed to be geographical differences in the diversity and incidence of indigenous BCAs, linked to variations in ecology, history of land use, agricultural practices and original biodiversity. The BCAs associated with each pest will be affected by whether the respective pest is indigenous or not in a given area. Where it is indigenous, it is likely to have more specialized BCAs present; where it is not indigenous, such BCAs will largely be absent. Even within individual countries, differences are likely to be large. IPM is often referred to as location-specific because it is based on the action of indigenous natural enemies, the composition and proportions of which vary at all scales.

**Classical biological control**. The movement of BCAs for classical biological control is largely

**Table 6. Origin of microbial and invertebrate biological control agents used in classical biological control of weeds**

| Origin | Number of classical biological control agents of weeds |
|---|---|
| Latin America and Caribbean | 197 |
| Europe | 165 |
| North America | 54 |
| Asia | 43 |
| Africa | 33 |
| Australasia | 28 |

*Source:* Data extracted from https://www.ibiocontrol.org/catalog/, accessed January 2020.

intercontinental. Although the transfer of BCAs within a continent takes place, for example from the east coast to the west coast of North America, this is relatively uncommon. All areas serve as sources of BCAs for classical biological control as shown in Table 5 for insect targets and Table 6 for weeds, although there are significant differences between regions.

**Augmentative biological control**. There are major geographical differences in the extent to which augmentative biological control is used (Tables 7 and 8), but the species used do not vary greatly between regions (van Lenteren, 2012; Klapwijk and Knapp, 2018; Ruidavets, Moerman and Vila, 2020). The scale of use seems to be more related to the investment made in the acquisition of BCAs in the respective region than to the availability of suitable indigenous BCAs or straightforward mechanisms for safely introducing non-indigenous BCAs. Between 2016 and 2019, the biocontrol market grew faster outside Europe than in Europe. IBMA figures show a 113 percent growth in the macrobial market outside Europe over this period, as compared to 70 percent growth in Europe, and a 399 percent growth in the microbial market outside Europe, as compared to 228 percent growth in Europe (IBMA, 2021).[14]

### 2.2.4. Monitoring

As alluded to above, there are significant gaps in taxonomic knowledge of BCAs, especially in less-

[14] Figures are based on data from 41 percent of IBMA members, representing 43 percent of market value.

**Table 7. The 2008 market share of commercial (i.e. predominantly in greenhouses) augmentative biological control by region**

| Continent | Market share (%) |
|---|---|
| Europe | 75 |
| North America | 10 |
| Asia | 8 |
| South America | 5 |
| Africa | 2 |

*Source:* Cock, M.J.W., van Lenteren, J.C., Brodeur, J., Barratt, B.I.P., Bigler, F., Bolckmans, K., Cônsoli, F.L., Haas, F., Mason, P.G. & Parra, J.R.P. 2009. *The use and exchange of biological control agents for food and agriculture.* Background Study Paper No. 47. Commission on Genetic Resources for Food and Agriculture. Rome, FAO.

developed countries. Without the ability to name and characterize BCAs, much monitoring is done at the genus or family level, which while useful is not as precise enough to allow different interventions to be assessed, implemented and evaluated. This impediment is most noticeable in the field of natural/conservation biological control, where in principle all species of natural enemies need to be considered in relation to their priority pests, whereas in classical biological control and augmentative biological control it is possible to focus taxonomic attention on particular species when needed. Even if taxonomic expertise is lacking for a particular group, molecular techniques (DNA barcodes and genome mapping) can be used to characterize species.

When a pest spreads from its indigenous area and is considered as a target for classical biological control or augmentative biological control, the first steps are a literature review and field surveys to identify the natural enemies in the area of origin and in the adventive range of the pest (i.e. the area into which it has spread). Literature reviews can be valuable where the pest is a serious problem in its area of origin. However, where this is not the case the literature is often inadequate, and field surveys will be needed, particularly when it comes to identifying which natural enemies have the biggest effect on the pest. There would be an advantage to surveying the BCAs of those pests identified as most likely to spread. So far this has rarely been done. However, New Zealand has recently pre-approved the conditional release of the parasitoid *Trissolcus japonicus* (Hymenoptera: Scelionidae) should its host, the brown marmorated stinkbug (*Halyomorpha halys*; Hemiptera: Pentatomidae) invade the country (EPA, 2018; Charles *et al.*, 2019). A similar approach is being explored in Australia (Caron *et al.*, 2021).

**Table 8. Area of field crops managed under major programmes of augmentative biological control in each continent**

| Continent | Area under control (x 1 000 ha) |
|---|---|
| Asia | 75 |
| South America | 10 |
| Africa | 8 |
| Europe | 5 |

*Notes*: Relatively small-scale use, under 30 000 ha not included. The figures should be considered indicative given that numbers are often rolled forwards without critical reassessment. The Asia figures exclude 10 million hectares in the former Soviet Union (probably largely in cotton production in Central Asia) for which no recent data were available and BCAs may no longer be produced.
*Sources:* Data extracted from van Lenteren, J.C., Bolckmans, K., Köhl, J., Ravensberg, W.J. & Urbaneja, A. 2018. Biological control using invertebrates and microorganisms: plenty of new opportunities. *BioControl*, 63: 39–59, and van Lenteren, J.C., Bueno, V.H.P., Luna, M.G. & Colmenarez, Y, eds. 2020. *Biological control in Latin America and the Caribbean: its rich history and bright future*. Wallingford, UK, CABI.

For classical biological control, there are several detailed regional global reviews cataloguing the use of introduced BCAs. However, most are now out of date (but see Julien, McFadyen and Cullen, eds, 2012; Van Driesche *et al.*, 2018; Schwarzländer *et al.*, 2018; van Lenteren *et al.*, 2020). Mason (ed., 2021) provides an up-to-date overview. The publication of up-to-date regional reviews would be desirable (e.g. Hill *et al.*, 2020). To some extent such reviews are being superseded by databases such BIOCAT (Greathead and Greathead, 1992; Cock *et al.*, 2016) and *Biological control of weeds: a world catalogue of agents and their target weeds* (Winston *et al.*, eds, 2014). These are important information sources. However, BIOCAT, in particular, lacks details and comprehensive sources. Ideally, databases should be available online and kept up to date. For the weed biocontrol catalogue,[15] this is the case. BIOCAT has been developed by CABI, but resources are needed to make it available on-line. For augmentative biological control, the new CABI Bioprotection

[15] https://www.ibiocontrol.org/catalog/

Portal[16] includes some information for the expanding number of countries.

## 2.3. Knowledge gaps

Where microorganisms are concerned, the main knowledge gaps that need to be filled relate to understanding of microbial diversity and how microbial communities are affected by human interventions, including by farming practices. Research on the design and implementation of improved ecosystem management practices is also needed. In relation to invertebrate BCAs, there is a major gap, or rather need for investment, globally in traditional and molecular taxonomy of pests and BCAs. Addressing this gap will provide the foundation for studies clarifying the roles and importance of different BCA species in different agroecosystems in different regions and for the development of measures for their conservation. It will also improve the predictability of conservation biological control strategies and the selection of the best BCAs for use in classical biological control and augmentative biological control.

[16] https://bioprotectionportal.com

# Chapter 3. State of management of biological control agents

This chapter consists of three sections, focusing on the state of three different aspects of the management of BCAs. The first addresses breeding for genetic improvement, i.e. the implementation of techniques for altering the genetic characteristics of populations with the aim of promoting the expression of desirable traits. The second addresses methods for increasing BCA populations for use via mass rearing in artificial environments or enabling their multiplication in natural environments. The third addresses conservation measures aimed at addressing threats to BCAs and ensuring they remain available for the future.

## 3.1 Breeding for genetic improvement

This section briefly introduces the topic of selective breeding of BCAs, considers the significance of genetic variation in mass rearing and selective breeding and discusses the state of knowledge and knowledge gaps in the field of genetic improvement.

### 3.1.1. Selective breeding

Selective breeding is not a new idea in biological control. Attempts began in the 1980s and primarily targeted insecticide resistance (for integrated pest control) (Hoy, 1986). However, because selective breeding requires considerable investments of time and biological knowledge, the standard practice in the past was simply to import a more effective BCA from the country of origin if needed. Following the entry into force of the Nagoya Protocol, there is a need to implement selective breeding more widely and more effectively (Lommen *et al.*, 2017; Lirakis and Magalhães, 2019; Bielza *et al.*, 2020; Leung *et al.*, 2020).

### 3.1.2. The significance of genetic variation in mass rearing and selective breeding

Selective breeding requires sufficient genetic variation for directional selection of a target trait. This implies a need to: 1) measure the existing genetic variation of the starter population; and 2) if genetic variation is low, identify and source individuals that can increase it. As well as being the raw material for selection, genetic variation is considered to be necessary in order to avoid the presumed deleterious effects of inbreeding.

This "bottom-up" approach based on measuring genetic variation is in fact rarely used. The common industrial practice in mass rearing is to take a phenotype-based top-down approach. The quality of products is spot-checked, which can involve counts to ensure a threshold number of individuals per lot or measuring field performance against a target pest with field assays or through user reportage (van Lenteren, 2003). If problems are observed, the population may be supplemented with backup individuals kept in diapause, or users may be given guidance on optimizing releases or on the use of additional or alternative BCAs. This approach does not provide information on the genetic variation within the population. Collecting data on the genetic variation of potential breeding populations (i.e. captive populations and wild populations already established in the region without requiring import) would allow better attribution of success or problems to this factor and provide an indication as to whether selective breeding should be considered (Ferguson *et al.*, 2020). A global database on the genetic variability of BCA populations would be a valuable resource, but it is unlikely that private interests would volunteer this information.

While classical and conservation biological control also require population build-up, commercial mass rearing is the hallmark of augmentative biological control (van Lenteren, 2012). Discussion about ABS effects on BCA breeding therefore centres on augmentative biological control. A repeated concern is the maintenance of genetic variation under the Nagoya Protocol (Lommen, de Jong and Pannebakker, 2017; Lirakis and Magalhães, 2019; Ferguson *et al.*, 2020; Leung *et al.*, 2020).

### 3.1.3. Key questions in the genetic improvement of biological control agents

#### 1) Does genetic variation exist in captive populations?

Genetic variation can be measured with molecular markers (most commonly by quantifying single nucleotide polymorphisms) or the percentage of heterozygosity across the genome (Höglund, 2009). For specific traits, the amount of phenotypic variation in a population that can be attributed to genetic variation is represented by heritability values (h2) (Visscher, Hill and Wray, 2008). A more recent concept is evolvabilty (CVA), the capacity of a system to evolve through selection (Kirschner and Gerhart, 1998). There is very little information on how much standing genetic variation exists in BCA populations. A recent systematic review for arthropod BCAs notes that out of more than 2 500 publications on adaptive selection, fewer than 70 mentioned an attempt to measure genetic variation, and fewer than 20 provided actual values (Ferguson *et al.*, 2020). This indicates that far more measurement is needed and that it should perhaps become a standard practice in the future.

### 2) What is the significance of low genetic variation?

It is generally acknowledged that genetic variation benefits a biocontrol population because it maximizes its adaptability to various applied environments and provides greater possibility for selective breeding (Wajnberg, 2004 and references within). However, to the present authors' knowledge, no mass-reared population has failed by dying out or losing control capacity because of inadequate genetic variation alone. There are two possible explanations for this. First, many BCA taxa have high inbreeding tolerance. For example, all parasitoid wasps are haplodiploid, and deleterious traits are quickly purged in the haploid state (Henter, 2003). Studies on BCA representatives from different insect orders (e.g. parasitoid wasps *Allotropa burrelli* [Quaglietti *et al.*, 2017] and Nasonia vitripennis [Luna and Hawkins, 2004], predators *Macrolophus pygmaeus, Chrysoperla externa, Cryptolaemus montrouzieri* [Quaglietti *et al.*, unpublished data] and *Podisus maculiventris* [de Clercq, Vandewalle and Tirry, 1998]) found no, or only minor, inbreeding depression for pest suppression, fitness and lifespan, and even some evidence for outbreeding depression (Luna and Hawkins, 2004; Vorsino *et al.*, 2012, Quaglietti *et al.*, unpublished data).

A second explanation is that inbreeding results in mass-rearing problems but has either not been detected or not been reported as the root cause. For example, inbreeding increases sterile diploid male incidence for some parasitoid wasps because of their sex determination system (the diploid male vortex; Zayed and Packer, 2005). Unfertilized eggs of parasitoid wasps will still develop into males, but fewer females with host-killing abilities are produced. Therefore, there are reductions in population fitness and pest suppression capability for the individual (Fauvergue *et al.*, 2015; Zaviezo *et al.*, 2018). However, there have been no reports of this inbreeding effect being problematic in biological control practice, perhaps because threshold production or pest-control levels were still met. While it does not currently seem to be a widespread problem, inbreeding has been documented as being in detrimental in certain contexts. For example, selection in the laboratory for flightlessness and corresponding inbreeding has reduced the reproductive abilities of the ladybird beetle *Harmonia axyridis* (Seko and Miura, 2009), although, confoundingly, in the wild this species has become highly invasive after inbreeding (a genetic bottleneck) purged deleterious alleles (Facon *et al.*, 2011). As inbreeding has also been harmful to BCA relatives (Henter, 2003), it should be evaluated as a potential threat for each taxon and each specific situation.

### 3) Assuming genetic variation is sufficient, what breeding outcomes are possible with artificial selection?

Selective breeding objectives can be divided into two broad categories, improving production and improving field performance. A BCA can thus be optimized for traits that result in higher fitness (more offspring), longer shelf life or higher pest-killing ability (Kruitwagen, Beukeboom and Wertheim, 2018; Lirakis and Magalhães, 2019; Leung *et al.*, 2020). Besides the need for sufficient genetic variation in the starter population, there are several other considerations. What exactly constitutes a "good" biological control trait and therefore an appropriate target for selection? Does the trait itself have high enough heritability to be passed on? Does the trait persist once selection is relaxed? Life history theory suggests that traits are improved at the expense of others (trade-offs): are there trade-offs that outweigh the benefit of selection?

It is possible that ambiguity about what traits should be selected for improved biological control and the required direction of the selection have hindered the genetic improvement of BCAs (Wajnberg, Roitberg and Boivin, 2016; Bielza *et al.*, 2020; Leung *et al.*, 2020). For example, should a BCA be selected for host-plant specialization and hence for efficacy on a specific crop or for generalized use on many crops to maximize its applicability? While such questions are difficult to answer, one solution may be to use modelling to identify the appropriate approach *a priori* (Wajnberg, Roitberg and Boivin, 2016). One such model explores the relative benefits of a lower dispersal strategy (to clear all pests in a single area) and a higher dispersal strategy (to incompletely reduce pests in more areas or a bigger one) (Plouvier and Wajnberg, 2018).

The history of genetic improvement of invertebrate BCAs has been thoroughly reviewed by Lirakis and Magalhães (2019). The available evidence indicates that selective-breeding programmes have generally been successful. Studies have a bias towards insecticide resistance (reflecting both concern about negative effects and interest in compatibility with integrated pest management), and overall study replication is lacking. However, selection for traits ranging from developmental diapause (which is used for BCA storage) to fecundity and host adaptation, has been persistently effective in many cases, even with selection relaxation (see references within Lirakis and Magalhães, 2019). The authors identify evolutionary trade-offs as the biggest problem and suggest designing selection regimes that are closer to natural conditions in order to prevent them. The scale of selective-breeding programmes is still very small, as they have mostly been limited to exploratory studies. There is no known bias with respect to the regions or countries conducting these studies, although a systematic review would be needed to confirm this.

#### 4) Beyond selective breeding, what other means are there for genetic improvement of BCA populations?

Several additional approaches are gaining traction for their utility in the post-Nagoya era. Some incorporate genetic variation and aspects of traditional artificial selection, and many can be used in combination. Some of these methods are still emerging and proof-of-principle studies demonstrating their feasibility and potential are needed.

Combining captive populations can increase genetic variation if new individuals cannot be sourced from the region of origin. There is even a suggestion that isogenic family lines could be created to preserve alleles so that they are not subsequently lost to drift (Roush and Hopper, 1995; Bai *et al.*, 2005), although this is not recommended for parasitoids with complementary sex determination, as this can actually cause line extinction (Zayed and Packer, 2005; Zaviezo *et al.*, 2018). There is some evidence that crossing dissimilar lines also results in hybrid vigour, for example increasing fecundity in the beetle *Longitarsal jacobaeae* (Szűcs *et al.*, 2012) and rescuing the pest-suppression ability of flightless *Harmonia axyridis* (Seko, Miyatake and Miura, 2012) (although, as previously noted, outbreeding depression is also possible; Luna and Hawkins, 2004; Vorsino *et al.*, 2012)

Genomic selection is a breeding approach in which the estimated breeding value of each individual for a trait is calculated based on a suite of genomic markers (Meuwissen, Hayes and Goddard, 2016). This can maximize the accuracy of defining breeding values. While this method has been used for livestock (Hayes *et al.*, 2009; Knol, Nielsen and Knap, 2016) and crops (Heffner, Sorrelles and Jannink, 2009; Crossa *et al.*, 2017), there are some challenges to its use in BCAs (Leung *et al.*, 2020). Most BCAs are too small bodied to allow a tissue sample to be taken for genotyping, and so the whole organism must be sacrificed. Siblings and offspring of the genotyped individual have to be used for actual breeding. Collecting the phenotypic data needed to assign value to each genetic marker (to set up the "reference population") might also be difficult, either in logistical terms or in terms of theoretical conceptualization, or both. For example, if the target trait is efficacious dispersal in the field, how should that be defined (i.e. greatest coverage or co-localization with the pest) and quantified (i.e. how can individuals be tracked)? A start might be made by using proxy, easier-to-measure traits, for example wing size as a proxy for dispersal (Xia, 2020).

Genetic modification has been repeatedly suggested for BCAs. The various categories of genetic modification are transgenics (moving genetic material from one species into another), knockdowns (temporary modification of gene expression with RNA) and knockout/knock-ins (permanent and heritable removal/addition of the function of a gene) (Leung *et al.*, 2020). While helpful for investigating the genetic architecture of biocontrol traits, it is unlikely that genetic modification will become common in biological control owing to its incompatibility with the "environmentally friendly" reputation of biological control, including in the context of organic production, and also because it is illegal in many countries other than the United States of America (Leung *et al.*, 2020). The need for long-term investment is also a constraint. An exception might be microbial (fungal and pathogenic) BCAs, which are both more amenable to genetic modification technologies and seem to invoke less controversy (Routray *et al.*, 2016; Scheepmaker, Hogervorst and Glandorf 2016; Karabörklü, Azizoglu and Azizoglu, 2017; Köhl, Kolnaar and Ravensberg, 2019).

Microbial manipulation has been explored from two perspectives: probiotic feeding (Ras *et al.*, 2017) and microbiome alteration to influence downstream phenotypes. Supplemental probiotic feeding has been used to increase mating success (Gavriel *et al.*, 2011) and immune response (Evans and Lopez, 2004). Changing the microbiome of BCAs themselves can have various phenotypic effects. A special class of bacteria, *Wolbachia*, is particularly notable for its presence across arthropods and for having a breadth of functions ranging from sex-ratio alteration to interspecies mating prevention, boosting metabolism and mediating disease (Werren, Baldo and Clark, 2008; Brinker *et al.*, 2019; Kaur *et al.*, 2021). Microbiome changes in the plants themselves can also make them less susceptible to pathogens (Massart, Margarita and Jijakli, 2015). They can also make a pest less susceptible to its predators (as with aphids with endosymbionts that can prevent the development of parasitoid offspring or prevent the host plant from releasing volatiles to recruit the parasitoids) (Frago *et al.*, 2017). The key is identifying the microbes that underlie desired effects. Often this begins by sequencing the microbiome of the organism, i.e. using markers to identify and quantify the relative composition of species present (the most prevalent are potentially the most important) (Ras *et al.*, 2017). The full possibilities of microbial manipulation remain to be seen and mass production techniques need to be developed.

### 3.1.4. Concluding remarks

The Nagoya Protocol may make it more difficult to source the genetic variation needed for BCA selective breeding, although there are certainly cases in which it has enabled exchanges that have allowed studies to take place while protecting the interests of the origin country (Smith *et al.*, 2018; Avilés-Polanco *et al.*, 2019). Selective breeding for specific traits has been successful, but it is largely confined to research. More advanced techniques, including genomic selection, have attracted some interest but their potential remains unclear. So far, the possibilities for sustaining genetic variation, enacting selection or improving mass rearing through innovative techniques are highly context dependent. They should be considered on a case-by-case basis as knowledge gaps are filled. The Commission could potentially play a role in maintaining databases that facilitate this process, for example an interactive site where importing and exporting countries could establish terms of exchange (e.g. for research materials) within the framework of the Nagoya Protocol, and a database tracking the genetic variation of populations available for selection programmes. For the first, perhaps the best start would be to build on the internal system used by CABI (Smith *et al.*, 2018) or to have a website analogous to that of the Convention on Biological Diversity (https://www.cbd.int/countries/?country=ao). This would require the relevant authorities within countries or regions to prepare standardized material of some kind for the database. The second would be much harder to establish, as there is no existing framework or indeed much existing interest in assessing the genetic variation of BCA populations. Perhaps the first step might be an information campaign explaining its importance and potential.

## 3.2 Mass-rearing of arthropod biological control agents

The mass-rearing of arthropods at commercial insectaries for field colonization for augmentative biological control of arthropod pests has a long tradition (van Lenteren, 2003), but it is less well developed for the classical biological control of weeds.

### 3.2.1. Mass rearing and collection of biological control agents for release

The ability to mass-produce large numbers of high-quality arthropod BCAs can be a tremendous asset when implementing a biological control programme (Halbritter and Wheeler, 2019; Wahl and Diaz, 2020). Releasing large numbers of BCAs usually allows faster population development, provides a larger gene pool to minimize genetic drift and increases the variability in the population and hence increases its ability to survive changing environmental conditions (Grevstad, 1999).

A rearing programme involves many challenges – the foremost including production of large numbers of high-quality BCAs at reasonable costs. In most cases, laboratory or greenhouse-based rearing is highly labour-intensive and therefore expensive, and severe space limitations often curtail the production of large numbers of BCAs (Moran *et al.*, 2014). In addition, there is a tendency when using such rearing methods to produce BCAs with genetic characteristics that may make them less suited for survival in field conditions, and thus more field-based mass-rearing methods are needed (Hill *et al.*, 2021).

BCA rearing facilities are used throughout the world (Table 9) and range from small laboratories rearing small starter colonies to large-scale tunnels or field plots that rear millions of individuals for augmentative releases. They may be non-profit operations, as is mostly the case for weed and arthropod classical BCAs, or they may be commercial operations, as is mostly the case for BCAs used in inundative releases targeting agricultural or forest pests. Under the Nagoya Protocol, the establishment of such enterprises can only be undertaken with appropriate benefit-sharing agreements in place with the country of origin of the BCAs (Mason *et al.*, 2018; Smith *et al.*, 2018).

The extent to which mass-rearing of classical BCAs is practised varies from country to country. In Australia, investment in the establishment of long-term mass-rearing and release "implementation" programmes has often had limited funding support. Some small-

**Table 9. Examples of mass-rearing of arthropod biological control agents**

| Target weed | Agent | Country | Reference | Notes |
|---|---|---|---|---|
| *Cynoglossum officinale* | *Mogulones cruciger* | Canada | De Clerck-Floate, Wikeem and Bourchier, 2005 | Houndstongue is grown as a field crop and *M. cruciger* is allowed to propagate freely within the crop for two generations before being collected for use. |
| *Pontederia eichhorniae* | *Neochetina eichhorniae and N. bruchi* | Australia | Julien, Griffiths and Wright, 1999 | Weevils are reared on plants grown in large pools, harvested regularly and released. |
| *Salvinia molesta* | *Crytobagous salviniae* | United States of America | Harms, Grodowitz and Nachtrieb, 2009 | Weevils are reared on plants grown in large pools, harvested regularly and released. |
| Several cacti species | Multiple agents | South Africa | Hill *et al.*, 2021 | Cochineal insects are reared on detached cladodes in tunnels. |
| Several aquatic weed species | Multiple agents | South Africa | Hill *et al.*, 2021 | Agents are reared on whole plants growing in pools in tunnels for temperature control. |
| *Chromolaena odorata* | *Calycomyza eupatorivora* | South Africa | Hill *et al.*, 2021 | Agents are reared on whole plants growing in tunnels for temperature control. |
| | *Lixus aemulus* | South Africa | Hill *et al.*, 2021 | Agents are reared on whole plants growing in tunnels for temperature control. |
| | *Dicrorampha odorata* | South Africa | Hill *et al.*, 2021 | Agents are reared on whole plants growing in tunnels for temperature control. |

*Source:* De Clerck-Floate, R.A. Wikeem B. & Bourchier R.S. 2005. Early establishment and dispersal of the weevil, *Mogulones cruciger* (Coleoptera: Curculionidae) for biological control of houndstongue (*Cynoglossum officinale*) in British Columbia, Canada. *Biocontrol Science and Technology*, 15(2): 173–190. https://doi.org/10.1080/09583150400016050; Julien, M.H., Griffiths, M.W. & Wright, A.D. 1999. Biological control of water hyacinth. *The weevils Neochetina bruchi and N. eichhorniae: biologies, host ranges and rearing, releasing and monitoring techniques for biological control of* Eichhornia crassipes. ACIAR Monograph No. 60. Canberra, Australian Centre for International Agricultural Research.; Harms, N., Grodowitz, M. & Nachtrieb, J. 2009. *Massrearing Cyrtobagous saliniae Calder and Sands for the management of* Salvinia molesta *Mitchell.* ERDC/TN APCRP-BC-16, October 2009. US Army Engineer Research and Development Center, Aquatic Plant Control Research Program.; Hill, M.P., Conlong, D., Zachariades, C., Coetzee, J.A., Paterson, I.D., Miller, B.E., Foxcroft, L. & Van Der Westhuizen, L. 2021. The role of mass-rearing in weed biological control projects in South Africa. *African Entomology*, 29(3): 1030–1044. https://doi.org/10.4001/003.029.1030

scale commercial mass-rearing operations periodically emerge in Australia.

In Canada, there are no federally dedicated personnel and laboratory facilities for large-scale propagation of weed or pest classical BCAs. National support for biological control implementation is instead research-based, with a focus on getting federal government approval for the importation and release of new BCAs and on developing release strategies to optimize their establishment. Federal biological control researchers typically establish BCA colonies at government facilities and rear enough for experimental releases.

The operational side of weed biological control in Canada, including the mass-rearing and distribution of BCAs, is typically implemented at the regional level by stakeholders with land-management responsibilities that include local weed control (e.g. provincial and municipal governments, producer and environmental organizations, transportation and energy companies, and First Nations groups).

In New Zealand, rearing of approved BCAs is funded by selling them to stakeholders on a cost-recovery basis. This has ensured that BCAs are widely released but has imposed some constraints on the numbers

**Table 10. Examples of dedicated field sites for the collection of biological control agents**

| Target weed | Agent | Country | Reference | Notes |
|---|---|---|---|---|
| *Tamarix spp.* | *Diorhabda* spp. | United States of America | Knutson *et al.*, 2019 | "*In situ*" "nursery" sites, protected from herbicide application, from which the *Diorhabda* beetles were redistributed to other sites. |
| *Melaleuca quinquenervia* | *Oxyops vitiosa* | United States of America | Center *et al.*, 2000 | Nursery sites were demarcated and protected from mechanical control. The beetle was collected at these sites and redistributed to other sites. |
| *Pontederia eichhorniae* | *Neochetina eichhorniae* and *N. bruchi* | United States of America | Diaz, pers. comm. | Large nursery sites from which large numbers of weevils can be collected and redistributed. |
| Waterweeds | Several agents | Australia | Purcell, pers. comm. | Water hyacinth, salvinia and water lettuce field sites that remained untouched, which facilitated the recruitment of agents. These were never officially demarcated. |
| *Acacia cyclops* | *Melanterius servulus* | South Africa | Moran, Hoffmann and Impson, pers. comm. | Biological control reserve set up by the landowner to allow the collection and redistribution of agents. |
| *Acacia mearnsii* | *Melanterius maculatus* and *Dasineura rubiformis* | South Africa | Moran, Hoffmann and Impson, pers. comm. | Biological control reserve set up by the landowner to allow the collection and redistribution of agents. |
| *Paraserianthes lophantha* | *Melanterius servulus* | South Africa | Moran, Hoffmann and Impson, pers. comm. | Biological control reserve set up by the landowner to allow the collection and redistribution of agents. |

*Source:* Center, T.D., Van, T.K., Rayachhetry, M., Buckingham, G.R., Dray, F.A., Wineriter, S.A., Purcell, M.F. & Pratt, P.D. 2000. Field colonization of the melaleuca snout beetle (*Oxyops vitiosa*) in South Florida. *Biological Control*, 19(2): 112–123. https://doi.org/10.1006/bcon.2000.085; Knutson, A.E., Tracy, J.L., Ritzi, C.M., Moran, P., Royer, T.A., & Deloach, C.J. 2019. Establishment, hybridization, dispersal, impact, and decline of *Diorhabda* spp. (Coleoptera: Chrysomelidae) released for biological control of tamarisk in Texas and New Mexico. *Environmental Entomology*, 48(6): 1297–1316. https://doi.org/10.1093/ee/nvz107

reared, as demand is relatively limited. In the United States of America, BCAs are mostly not mass-reared at all or are mass-reared for only a few years at the start of a field-release programme using targeted funding that ends once the BCA is established.

Mass-rearing and collection of BCAs for release is labour-intensive and thus expensive (Smith *et al.*, 2009). However, in South Africa, where there is a high unemployment rate, mass-rearing has been used to create jobs (Martin *et al.*, 2018). Between 2011 and 2020, some 4.7 million individual insects from 40 species of BCA were released onto 31 weed species at over 2 000 sites throughout the country. These insects were produced at mass-rearing facilities at eight research institutions, five schools and ten non-governmental organizations. The mass-rearing activities have created employment for 41 fulltime, fixed-contract staff, of which 11 have been people living with physical disabilities (Hill *et al.*, 2021).

There are far fewer examples of field rearing of BCAs (Table 10). Mostly these represent sites from which BCAs are routinely collected and redistributed to new infestations. Examples from around the world suggest that these sites seldom have any official demarcation as biological control reserves and are thus at the mercy of landowners and local authorities. In South Africa there is a provision under the Conservation of Agricultural Resources Act (Act 43 of 1983) that allows for the demarcation of biological control reserves for building up BCA populations. Unfortunately, this provision has seldom been utilized.

## 3.3 Conservation

The term "conservation" is taken here to refer to actions taken to reduce the risk of global or local extinctions of BCA species, to prevent population declines that reduce the supply of pest-control services or otherwise to prevent the loss of BCA diversity. Species used in classical or augmentative biological control are maintained through use (Section 3.2), both via mass-rearing in captivity and via various interventions to ensure that released populations flourish in the areas targeted. Populations maintained in this way are generally not in need of conservation in the sense of interventions to address the threat of extinction. However, wild source populations (and wild BCAs in general) may be threatened and hence need to be targeted by conservation measures. Conservation biological control (Section 1.2) involves interventions to encourage the presence of BCAs in and around production systems. Given that BCAs face various threats, including from unsustainable farming practices, it can be assumed that these interventions contribute to conservation (i.e. extinction-risk reduction) objectives. However, broader conservation measures may be needed to address threats to the species concerned.

*In situ* and *ex situ* conservation activities for microbial BCAs are discussed in the subsection below. In the case of invertebrate BCAs, while they may benefit from *in situ* conservation measures for biodiversity in general (e.g. declaration of protected areas or the introduction of biodiversity-friendly production practices) in areas where they are located, it is difficult to identify any conservation activities *per se* (i.e. beyond the various aspects of "use") that specifically target them.

### 3.3.1. Conservation of microbial biological control agents

As described in Chapter 2, the biodiversity found in and around production systems, including microorganism biodiversity, faces many threats. This gives rise to the need for conservation activities. In the context of the microorganisms that are natural enemies of pests and diseases, the aim is to conserve specific organisms, their communities and the habitats in which they flourish. There are several potential ways of achieving this, including both *in situ* and *ex situ* options. This section provides a snapshot of what is currently known about the conservation of microbial BCAs and makes recommendations for future actions in this field.

#### *In situ* conservation

Microorganisms in general, and microbial BCAs specifically, are rarely considered in conservation strategies. Their vast diversity, along with big knowledge gaps (as noted in Section 2.1, it is estimated that 99 percent are yet to be discovered), means that species-specific conservation is difficult to achieve in the natural environment. Not knowing exactly what it is you wish to conserve and the associated difficulties in monitoring may be one reason for the apparent impracticability of including microorganisms in conservation agendas (Cockell, 2008; Cockell and Jones, 2009). Better understanding of microbial communities and how they are affected by human activities such as farming and other ecosystem management practices is essential if effective conservation strategies are to be implemented.

Microorganisms feature in National Biodiversity Strategy and Action Plans (NBSAPs) produced in response to the Convention on Biological Diversity (CBD),[17] but for the most part the microorganism components of countries' biodiversity are overlooked or receive limited attention. Generally, the NBSAPs do not single out functions such as biological control. Most countries have not undertaken widespread assessments of microorganisms that have not yet been isolated and grown. The main current approach to conservation is the creation of protected areas, such as nature reserves or sites of special scientific interest, in the hope that this will maintain biodiversity (including microorganisms). Beyond protected areas, information is provided to farmers and other land managers on land-use practices that reduce impacts on biodiversity. This sometimes includes guidance specifically on practices that will enhance the reproduction, survival and efficacy of BCAs, including microbial pathogens (McCravy, 2008). There are also moves to reduce the use of chemicals that harm biodiversity, including

[17] https://www.cbd.int/nbsap

microorganisms. Any conservation programme needs to be supported by knowledge systems that provide information on best practice and protocols for implementation: see for example, the project funded by the Bill and Melinda Gates Foundation in which CABI and the Open Data Institute have engaged with national stakeholders to support data sharing with the aim of supporting innovation and improving decision-making in agriculture (Musker and Smith, 2021).

### *Ex situ* conservation

The conservation situation changes when individual microorganisms are isolated, subject to research and deliberately released for biological control purposes. Such strains may be maintained in researchers' laboratories or deposited in culture collections for safe keeping and future use. However, this does not always happen, and key strains can often be lost, for example because the most appropriate means of preservation is not employed or when researchers retire or research programmes end (Smith *et al.*, 2020). Once a strain is used commercially and sold as a product, its maintenance is given more consideration, and many private collections of production strains exist.

*Ex situ* conservation of microorganisms takes place at a number of levels. Researchers keep their own collections of microorganisms in private collections, and this may also happen at an institutional level. However, scientists are often reluctant to let others have the strains they utilize. When research is published, journal editors often advise that the strain on which it is based should be deposited in a public collection so that the science can be tested and further advances made (Stackebrandt *et al.*, 2014). However, this is usually not mandatory and capacity in collections is not infinite, and so strains are not always made available.[18] Public-service collections that have been established include the more than 120 collections that are affiliated to the World Federation for Culture Collections (WFCC),[19] which offer confidential safe-deposit services and provide for deposits in their open collections. Collection organizations are trying to improve their capacity and are working to provide a coordinated approach that better meets these needs.

It must also be recalled that, as recognized by the CBD, states have sovereign rights over their natural resources, and thus that the authority to determine access to genetic resources rests with national governments and can be subject to national legislation. An increasing number of countries have adopted access and benefit-sharing measures that require prior informed consent for access to their genetic resources for research and development purposes ("utilization") and the sharing of benefits derived from such utilization(Smith *et al.*, 2017; Hinz *et al.*, 2018; see also Chapter 4). ABS permits often also contain clauses on intellectual property protection. As a result of such ABS measures, the conservation of isolated, named, characterized and investigated strains is not complete, and potential microbial BCAs are not always available for further study and use.

Public-service collections, often referred to as microbial domain Biological Resource Centres (mBRCs) (see OECD, 2022a), preserve, store and distribute their holdings in compliance with the ABS requirements of the Nagoya Protocol. The WFCC-affiliated collections and mBRCs form part of the 800 plus collections listed by the World Data Centre for Microorganisms,[20] which together hold 3 293 403 strains (as of May 2021). These strains represent 42 106 species of bacteria and fungi from 78 countries and regions, which is less than 17 percent of the total known and described species (Paton *et al.*, 2020); this figure is only 0.7 percent of the total estimated number of microbial species (about 6.1 million). Unfortunately, details of all the strains are not available, but the Global Catalogue of Microorganisms (GCM) lists 480 819 of them, representing 55 828 species held by 133 culture collections in 50 countries and regions (http://gcm.wdcm.org/datastandards/). Microbial BCAs can be found among these holdings. They are not well labelled, and information is not easily found. However, it can be assumed that coverage of BCAs is at a similar level to microorganisms in general. Unfortunately, the data cannot be searched for organisms utilized as BCAs, but those isolated from insects can give some indication of their potential as BCAs; there are 905 species represented by 3 647 strains from 25 collections that were isolated from insects. The main genera of bacteria listed are *Acinetobacter, Bacillus, Burkholderia, Cryptococcus, Enterobacter, Klebsiella, Metschnikowia, Pseudomonas*. The main genera of fungi, including yeasts, listed are *Aschersonia, Aspergillus, Aureobasidium, Beauveria, Candida, Colletotrichum, Cordyceps, Dibromides, Entomophthora, Fusarium, Geotrichum, Hanseniaspora, Hirsutella, Hypocrea, Hypocrella, Isaria, Lecanicillium, Metarhizium, Mortierella, Nomurea, Ophiocordyceps, Paecilomyces, Penicillium, Phomopsis, Pichia, Polycephalomyces, Trichoderma* and *Verticillium*.

[18] In the case of invertebrate BCAs, researchers should be encouraged to deposit samples of the organisms they have worked on in entomological museums with published accession numbers and in a way that retains specimen integrity, particularly its genetic integrity, so that it can provide genomic data. However, storing dead organisms would clearly not amount to a form of conservation.
[19] www.wfcc.info
[20] http://www.wdcm.org

Technologies that can be used to observe microbial communities (microbiomes) are now available, and efforts are being made to store such communities and retain their functionality through the development of microbiome biobanks (Ryan *et al.*, 2020). As more is learned about the interactions of microorganisms and the importance of the microbiome, it is essential that this knowledge is taken into consideration in conservation strategies.

World Data Centre for Microorganisms (WDCM) statistics also demonstrate how the extent of holdings differs between regions, and in particular between developed and developing countries. The majority of the microorganisms held are in collections in Europe (256 collections holding 1 155 626 strains), North America (203 collections holding 606 000 strains) and Asia (296 collections holding 1 381 744 strains). The 42 collections in Oceania hold 125 587 strains and the 18 WDCM-registered collections in Africa, a continent of microbial megadiversity, hold just 17 422 strains.

There are efforts to strengthen and better coordinate microbial conservation activities (Smith *et al.*, 2020). It is essential that these efforts involve collaboration with policymakers, industry and academia to ensure that the investment made in isolating and characterizing strains by funding agencies is protected and that the products of the work are made available for future use. The Organisation for Economic Co-operation and Development (OECD) set up a task force at the beginning of the millennium to establish Biological Resource Centres (BRCs) (OECD, 2022a). In subsequent publications the OECD described BRCs as essential for the provision of resources for biotechnology and the bioeconomy (OECD, 2001). Over the years, operational best practice guidelines were developed and published by the OECD (OECD, 2022a). The guidelines emphasised that collaboration was needed to achieve optimal output, the premise being that no one collection or single country could provide the resources needed. The OECD endorsed the establishment of the Global Biological Resource Centre Network, an infrastructure intended to underpin advances in the biological sciences and their capacity to contribute to sustainable growth (OECD, 2022b). A proof of concept funded by the German Government provided a report on how this network could be established (Fritze, Martin and Smith, 2012), and efforts moved to the regional level, with the aim of creating the global infrastructure (Smith *et al.*, 2020), for example the launch of the Microbial Resources Research Infrastructure (MIRRI) in 2021 (see below).

Other organizations at national, regional and global levels are involved in coordinating *ex situ* conservation of microorganisms, including microbial BCAs. For example, the WFCC[21] is concerned with the collection, authentication, maintenance and distribution of cultures of microorganisms and cultured cells. Regional-level initiatives aimed at bringing together collections to operate to common standards and coordinate activities such as acquisition of strains include the following:

- in Europe, MIRRI,[22] a pan-European distributed research infrastructure for the preservation, systematic investigation, provision and valorization of microbial resources and biodiversity; and
- in Asia, the Asian Consortium for the Conservation and Sustainable Use of Microbial Resources (ACM),[23] which has established a task force to establish the Asian Biological Resource Centre Network (ABRCN).

Coordination at the national level strengthens the global network. There are over 20 networks of Microbial Resource Centres listed by the WDCM.[24] It is now time to bridge gaps between regional efforts (e.g. ABRCN, MIRRI) and national initiatives (e.g. the United States Culture Collection Network – USCCN)[25] and better coordinate all *ex situ* conservation activities for microorganisms. Partnering with biocontrol organizations would allow the development of strategies to improve the level of resources available. There is a need to analyse existing holdings of microbial BCAs, identify and address gaps in collections, and ensure strains are appropriately stored, maintained and made available for use.

Comparing the literature survey of published works presented in Section 2.2.1 to the numbers that are available from producers and public collections gives an indication of the extent to which the strains covered in the published works are available for further study and use. A thorough literature search would be needed to answer this question definitively. However, from the brief snapshot provided, it is clear that large numbers of the organisms cited in publications are not available. Stackebrandt (2010) estimated that of the strains cited in the first two issues of Volume 46 (2008) of the Journal of *Clinical Microbiology* (around 32 000 strains) and strains included in the publications of the 2008 volumes of ten European microbiology journals (listing

[21] http://www.wfcc.info/
[22] https://www.mirri.org
[23] https://www.acm-mrc.asia
[24] http://www.wfcc.info/collections/networks
[25] https://usccn.org/

**Box 2. Study on genetic resources for food and agriculture in the United Kingdom of Great Britain and Northern Ireland**

In 2004, the Department for Environment, Food and Rural Affairs (Defra) in the United Kingdom of Great Britain and Northern Ireland undertook a study on the establishment of an inventory for genetic resources for food and agriculture (GRFA) and scoped a GRFA information system (Defra, 2004). A snapshot of the status of conservation of animal, plant and microbial GRFA was presented. Analysis of data on microorganisms from the United Kingdom National Culture Collection, the United Kingdom Federation for Culture Collections, microbial scientific societies and a survey of microbial collections enabled the categorization of over 630 species as microbial GRFA. The 66 microbial collections surveyed had over 525 000 strains all told, but only around 100 000 of these were available electronically over the internet (ibid.). The resulting GRFA inventory was not complete and recommendations for further work were made. At the time, most of the 600 microbial species had representatives that were cryopreserved. However, the details of storage of the living material (fewer than 100 000 strains) were not fully available (ibid.). Follow-up work focused on plant and animal genetic resources and, as in many countries, the status of these resources is well covered, but actions on microorganisms remain unclear.

*Source*: Defra (Department for Environment, Food & Rural Affairs). 2004. *The establishment of an inventory for genetic resources for food and agriculture and scope a GRFA Information System: final summary report.* London

about 20 000 strains) only 0.03 percent had been deposited in collections.

As mentioned in Section 2.1.1, the analysis of data within CABI's BioProtection Portal,[26] a free, web-based tool that provides information on registered BCA products (microorganisms, invertebrate BCAs, natural substances and semiochemicals) showed that across 15 countries there were over 1 000 products utilizing over 950 BCAs in 38 genera of bacteria and fungi and a further 86 virus products. The assumption is that production strains are maintained by manufacturers for business continuity but that strains that have been studied for their potential use as BCAs and those that are not registered or selected are often discarded. It has been known for strains that could be important as future BCAs to be lost during storage. Further work is needed to obtain a complete picture of the status of conservation of BCAs. Box 2 presents an example of a national genetic resources study that surveyed the status of microbial collections.

Several collections focus on microorganisms of relevance to agriculture. In the private sector, the focus is on production strains and isolates with potential for use in the development of new plant protection products. In the public sector, collection strategies focus on storing and making available strains to support published science and research and the provision of services to industry so that it can maintain key strains. The main drivers for building such collections are company-based business continuity or individual or institutional goals; there are currently no national or international strategies coordinating activities with the aim of achieving comprehensive coverage and avoiding duplication of efforts.

### 3.3.2. Concludiing remarks

The global status of conservation measures for BCAs remains unclear. As noted above, in the case of invertebrate BCAs, it is difficult to identify any specific conservation activities. There is some information available for microbial BCAs, but the literature searches conducted for the present study found no comprehensive global reports. The lack of accessible data makes it difficult either to know where the specific gaps are or to provide an adequate overview. More work is needed to identify knowledge gaps and gaps in conservation coverage. Literature searches indicate that large numbers of microbial BCAs are known, with over 100 000 papers citing specific strains. However, numbers in collections are a long way short of such figures, with only 440 BCAs (at strain level) available commercially and up to 3 647 strains of invertebrate pathogens in the GCM. Where studies of conserved strains are more complete, it appears that less than 0.03 percent are deposited in culture collections. Such figures indicate that more needs to be done to assess current levels of *ex situ* conservation. More importantly, they also indicate the need to ensure all known BCAs are conserved. The various nomenclatural codes do drive the deposit of type strains (those upon which the description of the species is based), but properties are often strain-

[26] www.bioprotectionportal.com

specific, and there is no global effort to ensure that species diversity is conserved. A few collections clearly state that they hold microbial BCAs, but overall data are scattered and not easily accessed without considerable effort. This study focused on the integrated catalogue of the WFCC.

Maintenance of microbial BCAs *ex situ* is inadequate and insecure, except for those being maintained as sources of currently marketed products. The private sector has strategies for ensuring that such stocks are maintained, but beyond this conservation is poorly addressed. Some potential tools are available and there are some coordinated activities, but a coordinated strategy is needed. Cooperation between key players – the private sector, research funders and governments – is required. Not all organisms can be maintained *ex situ*. However, combining the approach with *in situ* measures and the storage of representative microbiomes in cryopreserved samples can provide an inclusive conservation strategy. Journals and research-programme funders could insist that microorganisms are stored for future use.

# Chapter 4. Policies and instruments for the sustainable use and conservation of biological control agents

The sustainable use and conservation of biodiversity for food and agriculture are facilitated by policies and other instruments of government. However, there has never been a review of the types of policies and instruments that directly or indirectly specify BCAs as a constituent of the biodiversity covered or of how implementation of such policies and instruments may affect (enable or disable) the sustainable use and conservation of BCAs. Therefore, there is a need to identify BCA-related policies and instruments that can serve as models for governments that wish to act to ensure the sustainable use and conservation of BCAs.

## 4.1 General overview

The sections below provide an overview of relevant policy and regulatory instruments at global, regional and national levels. Relevant components of these instruments are highlighted, and how they can potentially contribute to the promotion of biological control is discussed, focusing both on the direct management of BCAs and on how threats affecting them can be addressed.

### 4.1.1. International instruments

#### IPPC International Standards for Phytosanitary Measures

In 1951, the International Plant Protection Convention was established under the auspices of FAO to provide globally coordinated action to prevent and control the introduction, establishment and spread of crop pests and thereby protect (cultivated, native) plants. Under IPPC, the Commission on Phytosanitary Measures develops and adopts International Standards for Phytosanitary Measures (ISPMs), which are recognized by the World Trade Organization (WTO) as the basis for trade-related phytosanitary measures. These range from frameworks for pest risk analysis (ISPM 2) to guidelines for pest surveillance (ISPM 6). A number of ISPM standards directly relate to biological control (Sheppard *et al.*, 2019). Though these international standards are not legally binding, they can inform the development of countries' phytosanitary policies. Overall, ISPM 3 relates to the export, shipment, import and release of BCAs – and has proven to be a sound framework for formalizing good practice and providing country-level guidance on biological control (Kairo *et al.*, 2003). The movement of samples/material between countries has to comply with the export/import rules of both donor and recipient, thus encouraging intercountry collaboration and harmonization of approaches to biological control. ISPM 3 was first endorsed in 1995 as the "Code of Conduct for the Import and Release of Exotic Biological Control Agents".

#### Convention on Biological Diversity

The Convention on Biological Diversity (CBD) was adopted in 1992 at the Earth Summit in Brazil, entered into force in late 1993 and currently has 196 parties. The objectives of the CBD are conservation and sustainable use of biodiversity and the fair and equitable sharing of benefits arising from the utilization of genetic resources. At present, the CBD is primarily implemented through NBSAPs.

The management of BCAs is relevant to all three of the CBD's objectives. As discussed in Chapter 2, many BCAs are under threat from various drivers and may require conservation measures of various kinds (Chapter 3). With regard both to conservation and sustainable use, biological control provides a "biodiversity-friendly" solution for pest control and invasive species management and can thus be a key component of NBSAPs. ABS is covered under Article 15 of the CBD and through the supplementary Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity (Nagoya Protocol). Parties to the Nagoya Protocol must develop a legal framework to ensure the fair and equitable sharing of the benefits that arise from the utilization of their native genetic resources (see Section 4.5 for further discussion). Given that augmentative and classical biological control use genetic resources from specific jurisdictions (providers) for deployment in other parts of the world, the sourcing of microbial and invertebrate BCAs to be used for research and development will often trigger access and benefit-sharing obligations enacted in line with the Nagoya Protocol.

Looking ahead, the Post-2020 Global Biodiversity Framework provides an opportunity to eliminate some (perceived) hurdles, to harmonize approaches between countries and regions, and ultimately to ensure biological control is optimally wielded to protect global biodiversity.

### Stockholm Convention on Persistent Organic Pollutants

The Stockholm Convention on Persistent Organic Pollutants (POPs), signed in 2001 in Stockholm, Sweden, was ratified by an initial 128 parties and entered into force on May 2004. As a multilateral agreement, the Stockholm Convention aims to protect human health and the environment from a range of persistent organic pollutants including several chemical pesticides. Initially, the Convention focused on 12 POPs (the so-called “dirty dozen”), most of which were agrochemicals, such as Aldrin, Dieldrin and DDT. Aside from placing a global ban on several harmful compounds, it also required its signatories to take measures to eliminate or reduce the release of POPs into the environment. Though the Stockholm Convention does not refer specifically to biological control, it does recognize the importance of environmentally sound alternative processes and chemicals. It further requires its parties to raise public awareness and incentivize research, development and cooperation on alternatives. For certain POPs, parties are also urged to research and develop alternative non-chemical products, methods and strategies.

### Rotterdam Convention

The Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade is a multilateral agreement that was signed in 1998, entered into force in February 2004 and currently has 161 Parties. The Convention aims to promote shared responsibility, cooperation and information exchange in the international trade of hazardous chemicals, including several pesticides. Again, though the Convention does refer directly to biological control, it does urge its parties to share information and to engage in public awareness-raising regarding the availability of alternatives that are safer for human health or the environment. In principle, this could cover conservation, classical and augmentative biological control.

### International Code of Conduct on Pesticide Management

FAO first published a set of guidelines covering the efficacy data required for registration of pesticides in 1985. In 2006, these guidelines were updated to provide better guidance to pesticide producers and national governments alike on the design, conduct and evaluation of pesticide efficacy trials (FAO, 2006). The guidelines focused primarily on synthetic pesticides intended for plant protection, though brief mention was also made of microbial BCAs (bacteria, algae, fungi, viruses and protozoa). Although the extent of efficacy data required for biological control products was similar to that required for chemical compounds, special consideration was to be given to environmental conditions, viability, chemical characteristics and the availability of reference products. Macrobial BCAs (e.g. nematodes, mites, parasitoids and predators) were not covered by the 2006 guidelines.

The FAO/WHO International Code of Conduct on Pesticide Management (WHO and FAO, 2014) is a voluntary framework on pesticide management endorsed in 2013. It is intended for use by all public and private entities engaged in, or associated with, production, regulation and management of pesticides (FAO, 2021). The standards of conduct set out in the code adopt “the ‘life-cycle’ approach to management of pesticides to address all major aspects related to the development, registration, production, trade, packaging, labelling, distribution, storage, transport, handling, application, use, disposal and monitoring of pesticides and pesticide residues as well as management of pesticide waste and pesticide containers” and are intended to promote IPM and integrated vector management (WHO and FAO, 2014). The code calls on governments to “encourage and promote research on, and the development of, alternatives to existing pesticides that pose fewer risks such as biological control agents and techniques” (ibid).

Various technical guidelines and other resources elaborating on specific elements of the International Code of Conduct have been published (FAO and WHO, 2021). These include the *Guidelines on best practice in the registration of micro-organisms, botanicals and semiochemicals for plant protection and public health* (FAO and WHO, 2017). This publication focuses primarily on data requirements for registration and evaluation approaches. It provides national authorities with a framework for registering biopesticides, identifies aspects in which they differ from chemical pesticides, and notes issues to which registration authorities need to pay special attention. In keeping with the principles and processes of the Guidelines for the Registration of Pesticides (FAO and WHO, 2010) and the Guidelines on Data Requirements for the Registration of Pesticides (FAO and WHO, 2013), it aims to ensure that evaluations and decisions with regard to registration of the above products provide an appropriate level of protection for human and animal health and for the environment. Also of direct relevance to BCA management are the *Guidelines on highly hazardous pesticides* (FAO and WHO, 2016), which refer to several steps that can be taken to promote the use of biological control as a low-risk alternative.

### 4.1.2. National and regional legal and policy frameworks

#### Crop protection product registration, post-registration and trade

Examples of measures addressing registration of and trade in BCAs include the regulatory framework developed in 2012 by the Association of Southeast Asian Nations (ASEAN), supported by the German Technical Cooperation, GIZ, with the intention of easing market access to and use of BCAs, including biopesticides. With support from FAO and technical inputs from the International Biocontrol Manufacturers' Association (IBMA), a team of regulatory and application experts prepared the *ASEAN Guidelines on the Regulation, Use, and Trade of Biological Control Agents* (BCA) (Lim *et al.*, 2014). This document aimed to harmonize legislation on BCAs across the region. Following its endorsement by the Agricultural Ministers of ASEAN, the number of BCA registrations has increased in countries such as Indonesia, Thailand and Viet Nam (Jäkel, 2017).

The North American Plant Protection Organization (NAPPO) has harmonized information requirements for invertebrate BCAs in the region (Sheppard *et al.*, 2019; Barratt *et al.*, 2021). This cross-jurisdictional streamlining of registration procedures and data needs can cut costs, bolster the assurance of the human and ecological safety of BCAs and ultimately accelerate farmer uptake. NAPPO's biological control expert group (comprising members of research entities, regulatory bodies and the private sector) has detailed the data requirements for Canada, Mexico and the United States of America – based upon ISPM standards. As a result, three Regional Standards for Phytosanitary Measures (RSPMs) were formulated in 2015: RSPM # 7 "Guidelines for Petition for First Release of Non-indigenous Phytophagous or Phytopathogenic Biological Control Agents"; RSPM # 12 "Guidelines for Petition for First Release of Nonindigenous Entomophagous Biological Control Agents"; and RSPM # 26 "Certification of commercial arthropod biological control agents or non-Apis pollinators moving into NAPPO member countries". Though the above RSPMs specify the minimum data requirements for a submission to a NAPPO regulatory agency, additional requirements may apply for specific countries. Moreover, while each NAPPO Member country has its own review panel, experts from all countries are consulted and information is routinely exchanged among national regulatory entities.

In 2003, it was acknowledged that Kenyan farmers' reliance of synthetic pesticides had caused harm to the country's environment. Several stakeholders came together with the aim of enabling faster registration (and enhanced use) of BCAs. This resulted in Kenya's pesticide legislation (Pest Control Products Act, Cap 346, 1982) being amended so as to include regulatory provisions specifically for microbial and invertebrate BCAs, botanical pesticides and semiochemicals. Implementation of the amended legislation has resulted in an increase in the availability of biological control products to farmers. It has recently also been used as a model in other countries of the East African Community.

#### Pesticide risk assessment and regulation

Insecticide resistance is a topic of global concern, with more than 600 insect and mite species currently showing resistance to at least one synthetic pesticide (Jørgensen *et al.*, 2018; Sparks *et al.*, 2020). A staggering 335 pesticide active ingredients have at least one documented case of resistance worldwide. Insecticide resistance management (IRM) is an approach used to promote the long-term efficacy of pesticidal compounds and slow (or avert) the gradual decline in organismal susceptibility to existing and future synthetic biocides. Fungicide resistance management schemes are built on the same principles. Since 1984, the Insecticide Resistance Action Committee (IRAC) has led a globally coordinated campaign on IRM – largely representing the interests of the agrochemical industry. The Fungicide Resistance Action Committee addresses the same issues for fungicides. IRAC's IRM strategy is primarily centred on the active rotation/alternation of insecticide modes of action (MoAs), and it is only recently that BCAs have been incorporated in the MoA classification schemes. This represents an opportunity to promote all forms of biological control under an IPM umbrella and to gradually lower the need for pesticide-based measures.

The European Food Safety Authority (EFSA) has put forward a new approach to environmental risk assessment for honey bees (EFSA Scientific Committee *et al.*, 2021). In response to a request by European Parliament's Committee for the Environment, Public Health and Food Safety, a holistic framework has been proposed for assessing the combined effects of multiple stressors on honey-bee health and fitness. By enabling precise assessment of (multiple) pesticides and other stressors, this framework has the potential to bolster environmental risk assessment approaches, help mitigate pesticide-induced impacts and ultimately create momentum for biological control.

### Ecological safety of biological control agents

a. EPPO Standard on Import and Release of Non-indigenous Biological Control Agents

The European and Mediterranean Plant Protection Organization (EPPO) manages a set of regulations and standards that affect both augmentative and classical biological control (Hoeschle-Zeledon, Neuenschwander and Kumar, 2013). If the initial importation of a BCA for research or mass-rearing is being considered, EPPO Standard PM 6/1 "First import of exotic biological control agents for research under contained conditions" applies. In other circumstances (e.g. when an organism is being imported for direct release), a dossier needs to be submitted to the relevant national authority. A decision is then made on whether the anticipated introduction should be subject to pest risk analysis in accordance with existing ISPM standards. Potential environmental impacts (e.g. on non-target invertebrates) are given due consideration. To facilitate the process, the EPPO/IOBC Panel on Safe Use of Biological Control Agents maintains a positive list of BCAs that are already used within Europe. The panel has also further refined EPPO Standard 6/2(3) "Import and release of non-indigenous biological control agents".

b. National standards

To date, five countries (Australia, Canada, New Zealand, South Africa and the United States of America) have undertaken the bulk of classical biological control efforts (Sheppard and Warner, 2017). These countries have adopted regulatory processes to ease the introduction of exotic BCAs while ensuring agile, but thorough, assessment of associated ecological risks (and, occasionally, societal benefits). While the regulatory processes in these countries differ markedly (e.g. Hunt *et al.*, 2008; Barratt *et al.*, 2021), much can be learned from the policy tools that are in place in Australia and New Zealand to address trade-related biosecurity risks. These tools help provide a balance between facilitating international trade ensuring the ecological safety of new biological introductions. New Zealand requires a joint assessment of both the risks and the benefits of classical biological control, while Australia does not consider benefits as part of the standard regulatory process (Sheppard *et al.*, 2003). Australia is currently the only country to have legislation specifically addressing biological control, the 1984 Biological Control Act – through which some legal protection is provided for government agencies involved in BCA releases that potentially carry some (ecological) risk. In New Zealand, all biological introductions are regulated under the Hazardous Substances and New Organisms Act 1996 (HSNO) – which aims to preserve the health and safety of the country's people and natural environment. Regulation is based on a scientifically informed dialogue, with BCA introductions considered justified once the anticipated societal benefits outweigh the risks.

### Integrated pest management

a. National IPM training programmes

With FAO support, several Asian countries embarked on national IPM training programmes during the 1980s and 1990s. In response to pesticide-triggered outbreaks of the rice brown planthopper and related socioeconomic impacts, the Indonesian Government released a Presidential Decree in 1986 banning several insecticide compounds, eliminating government subsidy schemes and declaring IPM to be the national crop-protection policy (Hammig *et al.*, 2008). Aside from leading to sharp reductions in pesticide use, IPM training programmes lowered pest numbers and enhanced crop yields. Indonesia's IPM programme cut pesticide-related expenditures by USD 80–120 million/year by the late 1990s (Kenmore, 2006). These policies took root in several Asian countries and were tied to FAO-run farmer field school (FFS) programmes. Relative to conventional practice, FFS programmes reduced the environmental impact of agriculture by 39 percent and raised farmer profits by 19 percent (Van den Berg and Jiggins, 2007; Waddington *et al.*, 2014).

b. European Commission's 2030 Green Deal and Farm-to-Fork strategy

In recent years, several comprehensive policy frameworks have emerged that place major emphasis on environmental health instead of on everlasting accrual of profits and limitless growth (European Commission, 2020). Europe's Green Deal comprises the Farm-to-Fork strategy, which targets a 50 percent reduction in the use of chemical pesticides and 25 percent total coverage of organic production by 2030. Biological control could be a core ingredient in this decade-long programme and create ample spin-offs for European farmers, society and the environment (Hulot and Hiller, 2021). The programme potentially allows the benefits of biological control to be fully reaped, for example by adapting EU legal frameworks so as to recognize biological control's non-toxic aspects (as compared to chemical pesticides) or by demonstrating its true potential through large-scale field application and evaluation. Other elements – primarily related to the envisioned EU agroecological transition (Lampkin, Schwarz and Bellon, 2020) – also favour certain forms of biological control. These include fostering diversification of agrifood production systems, bolstering farm-level resilience and improving the integration of biodiversity and habitat conservation within agricultural production systems.

### 4.1.3. Other notable initiatives

#### 1. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

In 2012, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) was established as an intergovernmental organization working to improve the science-policy interface on ecosystem services and biodiversity-related matters. In its recent global report on biodiversity and ecosystem services, IPBES concluded that input-intensive, industrial farming systems is one of the prime drivers of biodiversity loss (Díaz *et al.*, 2019). To avoid the negative externalities of agriculture and prevent system lock-ins, for example for pesticide use among smallholder farmers (Wagner, Cox and Bazo Robles, 2016), more sustainable approaches to farming, such as agroecology, need to be upscaled. While these measures can directly bolster natural pest control, there is also ample room for other forms of biological control (e.g. Van Driesche *et al.*, 2010). Following an earlier IPBES report on the precipitous decline of pollinators (IPBES, 2016), a "Coalition of the Willing" was formed to draw up national plans to protect them. Given that nature-based pest control methods are core elements of a proposed insect recovery roadmap (Harvey *et al.*, 2020), biological control could – but rarely does – feature prominently in pollinator conservation plans. IPBES has also emphasized the growing threat of invasive alien species (IAS) to biodiversity, ecosystem services and human well-being. Classical biological control constitutes a tailor-made solution for the sustainable management of IAS. At the same time, other forms of biological control represent desirable alternatives to pesticide-based IAS mitigation. For example, habitat management and conservation biological control can bolster the resilience of ecosystems and thereby lower the likelihood of IAS establishment or spread.

## 4.2 State of national policies and instruments

The sections below describe how the implementation of policies and regulatory instruments at the national level can have a disabling or enabling effect on biological control. They spotlight regulatory instruments that enable the uptake of conservation, classical and augmentative biological control, drawing on experiences from across the globe.

### 4.2.1. Conservation biological control

Area-wide pest management programmes, such as those ones backed by FAO–IAEA (International Atomic Energy Agency), can greatly benefit conservation biological control (Hendrichs, Pereira and Vreysen, eds, 2021). Top-down initiatives involving scheduled releases of laboratory-reared parasitoids and sterile males of Tephritid fruit flies aim to boost the export of tropical fruits from Belize, Guatemala and Mexico (Salcedo-Baca *et al.*, 2013). Initially set up through development assistance from the United States of America, support from the respective national governments and contributions from growers, these programmes have been in place since the late 1970s. Reducing insecticide inputs over more than 30 years has bolstered natural biological control, restored pollination services worth USD 64.9 million and increased sales of products derived from honey bees. Similarly, in the mid-1900s, natural biological control was fortified in the United States of America through the Huffaker project and the subsequent IPM consortium through which 70–80 percent pesticide cuts were attained on more than 5 million hectares of farmland (Pimentel and Peshin, 2014). Area-wide pest management programmes continue to be in place in Brazil, China and the United States of America, tailored for example to cotton or sugar-cane production.

The uptake of biological control can be enhanced by detailing so-called "stacked" ecosystem services and pursuing synergies with biodiversity conservation, tourism or recreation, (Fiedler, Landis and Wratten, 2008). In the United Kingdom, researchers investigated whether habitat management (e.g. beetle banks) could raise the population levels of game birds such as grey partridge. These farmland habitats are easy and cheap to establish, raise natural enemy numbers and simultaneously provide nesting cover for the birds (Thomas, Goulson and Holland, 2001). When the predecessor of Defra designed policies to reverse the decline of farmland birds, various agrienvironmental schemes were promoted including beetle banks (Grice *et al.*, 2004). Though only a fraction of farmers initially deployed these structures, the initiative helped translate biological control research into policy and practice, and permitted the engagement of non-traditional stakeholders, such as hunters, birders and wildlife conservationists.

Many developing countries encounter difficulties in effectively transferring regulatory models from the international arena to the national level. While global, FAO-endorsed agreements call for restriction of hazardous pesticides, such topics regularly get sidelined in national policy agendas (Jansen , 2008). The way in which pesticide risks are framed often leads national decision-makers to dismiss calls for tighter regulation as founded on ignorance. Specifically, the "safe use" frame and the "technology-assessment" frame regularly obstruct progress. The former argues that pesticides are intrinsically safe and essential for agrifood production, while the latter reflects the way agronomists in regulatory agencies aspire to technical correctness. As a result, pesticide-based farming approaches continue to prevail and hamper the uptake of conservation biological control. This hurdle can potentially be circumvented by underlining the "superior" safety of the latter approach or by incorporating technical expertise and tailored regulatory procedures for biological control products (see below). Tailored messaging on the efficacy and cost-effectiveness of non-chemical alternatives such as conservation biological control is equally important (Naranjo, Ellsworth and Frisvold, 2015; Wyckhuys *et al.*, 2020a). Facilitating access to online toolkits that list selective pesticides, for example IOBC's pesticide side-effects database, could help broaden the selection criteria of national regulators (IOBC, 2021). A guideline on the selection of low-risk compounds recently developed by Jepson *et al.* (2020) could potentially complement technical details on pesticide efficacy.

Other potential enablers include national (or state-level) legislation developed to protect honey bees or insect pollinators in general. In 2019, the Mexican state of Guanajuato adopted a law to protect honey bee-dependent businesses – imposing fines of up to 8 000 Mexican pesos (USD 400) on those causing damage to individual bees or beehives. In March 2021, government decision-makers in Mexico unanimously approved a similarly inspired Federal Beekeepers Law, intended, *inter alia*, to minimize agriculture-related impacts on pollinators (Cámara de Diputados, 2021). All forms of biological control could play a considerable role in its "real-world" implementation and enforcement.

### 4.2.2. Augmentative biological control

A set of conferences organized by the Inter-American Institute for Cooperation in Agriculture (IICA) during 2020 carried out an in-depth assessment of drivers of augmentative biological control in Argentina, Brazil, Colombia, Ecuador and Mexico (Goulet and Krotsch, 2020). Though myriad factors shape uptake trajectories in the five countries, a favourable policy environment is crucial. The following elements were identified as key success factors: 1) adaptation of regulatory frameworks to facilitate registration of biological control agents and products; 2) creation of space for commercial biological control manufactures; 3) encouragement for safe and good-quality cottage-style production of BCAs by individual farmers or grower cooperatives; and 4) an active role of government in crafting and implementing integrated policies to promote non-chemical pest control. The latter is reflected in the enactment of fully fledged national programmes or plans (e.g. Comité Asesor en Bioinsumos de Uso Agropecuario [CABUA] in Argentina and Programa Bioinsumos in Brazil). The best example of state-supported mass-rearing of natural enemies continues to be Cuba's 1993 Programme for Agroecological Pest Management. Its nationwide establishment of Centers for the Reproduction of Entomophages and Entomopathogens not only made Cuba a showcase for biological control but also inspired similar initiatives in countries such as Brazil, Mexico, Peru, Thailand and Viet Nam.

Over the past decades, several national and regional IPM regulations have been devised across the globe. In order to avoid potential misinterpretation and thus delay biological control implementation, these different instruments should ideally be simplified and harmonized (Bolckmans, 1999). For example, Europe's Regulation 1107/2009/EC and Directive 2009/128/EC were designed to streamline the registration of plant-protection products, including (microbial) BCAs. The former regulation pursues EU-wide harmonization of registration procedures through the establishment of a two-tier system in which a given active ingredient is first approved at the EU level for subsequent product authorization by Member States. Regulation 1107/2009/EC stipulates that authorizations granted by one Member State should, in principle, be accepted by others with comparable agroclimatic and phytosanitary conditions. In other parts of the world (e.g. Africa), such harmonized regulations are not in place (Hoeschle-Zeledon, Neuenschwander and Kumar, 2013; Barratt *et al.*, 2018).

To promote augmentative biological control, individual countries can waive registration requirements for indigenous natural enemies and other beneficial organisms (Hoeschle-Zeledon, Neuenschwander and Kumar, 2013). This has been taken to heart by countries, such as China, where the establishment of a "green" channel – through which fast-track registration (or exemption) of invertebrate or microbial biological control products would be enabled – is being considered. In Kenya, the national Pest Control Products Board has developed specific registration pathways for biopesticides (including microbial products) and BCAs (Gwynn and Maniania, 2010). Waivers can be granted for ecotoxicological data when evidence shows that, for example, exposure to certain non-target organisms is unlikely. At least two seasons of efficacy trials are required, with the time from pre-consultation to registration of a microbial pest-control product taking roughly two to four years (ibid). In the United States of America, priority registration of low-risk natural enemies and biopesticides has been in place for several years. Other enablers include the provision of biological control subsidies to growers in European countries and Denmark's application of pesticide levies (van Lenteren *et al.*, 2018).

A noteworthy initiative aimed at promoting both augmentative and conservation biological control is Viet Nam's 2003 Three Reductions, Three Gains (3G3T) policy (Huan *et al.*, 2008). This programme emphasized reducing the use of synthetic fertilizer and seed inputs and refraining from the use of insecticides during the first 40 days after crop establishment. After extensive field-testing and scientific validation (e.g. with support from the International Rice Research Institute), a mass-media campaign effectively transferred this approach to millions of Vietnamese rice farmers (Heong *et al.*, 2013). In 2015–2016, German-run programmes showed that applications of entomopathogenic fungi were highly compatible with 3G3T approaches and further fortified natural biological control in Viet Nam's rice paddies (Jäkel, 2017).

Lastly, the diffusion of augmentative biological control can be enhanced by raising public awareness or by providing farmers with access to information on biological control. For example, Peru's phytosanitary authority Servicio Nacional de Sanidad Agraria (SENASA) recently launched an online, open-access portal that contains "digestible" information on the types and usage modes of nationally registered biopesticides. This information can be readily consulted by farmers, pest-management professionals and extension agents.

### 4.2.3. Classical biological control

Intergovernmental and other international collaboration, adherence to international regulations, efficient use of research facilities and increased training of biological control practitioners can all be important enablers of classical (and other forms of) biological control. This is exemplified by the swift introduction of the specialist parasitoid *Epidinocarsis lopezi* for control of the invasive cassava mealybug across Southeast Asia. Less than one year after the mealybug's detection in the country's main cassava-growing region in 2008, the Government of Thailand opted to import the parasitoid wasp from CGIAR centres in Benin (Winotai *et al.*, 2010). After quarantine procedures and laboratory- and field-tests were conducted in line with ISPM 3 guidelines, mass-rearing and countrywide releases (some by aeroplane) of *E. lopezi* wasps were initiated. This endeavour was enabled by seamless cooperation between FAO, CGIAR centres, multiple government institutions, grower associations and private sector actors, including the Thai Tapioca Development Institute. By May 2012, millions of parasitoids had been released across the country, while releases facilitated by FAO or CGIAR (or both) were carried out in nearby Cambodia, Indonesia, the Lao People's Democratic Republic and Viet Nam over the period 2012 to 2014. Despite internal efforts to push prophylactic dips of neonicotinoid insecticides (Parsa, Kondo and Winotai, 2012), *E. lopezi* wasps drove down mealybug populations and now save Asia's cassava sector USD 3.5 billion to USD 5 billion annually (Wyckhuys *et al.*, 2018b, 2020b).

During the past century, a small number of misguided introductions for the "biological control" of pests (e.g. the 1935 introduction of cane toads into Australia) resulted in significant undesirable ecological impacts. As a result, the ecological risks of biological control have received disproportionate attention from scientists, decision-makers and the general public since the early 1990s (Heimpel and Cock, 2018). This led to a steep drop in biological control introductions, risk-averse attitudes across various segments of society and the development of (often excessively stringent) risk-assessment procedures. The latter have delayed or even prevented the launch of new programmes in many parts of the world and thus have given rise to major opportunity costs (Heimpel and Cock, 2018). To ease a transition towards a new paradigm whereby the benefits and risks of biological control are explicitly balanced, countries such as New Zealand require applicants to clearly articulate the advantages of biological control (as compared to other approaches such as those based on pesticides) (Sheppard *et al.*, 2019). Though doing so goes beyond what is compulsory for most countries, and may be costly and time-consuming, it ultimately averts important costs and conflicts.

The CBD ABS arrangements that are in place in numerous countries constitute a second obstacle to the development of both augmentative and classical biological control (Coutinot *et al.*, 2013; Smith *et al.*, 2018; Silvestri *et al.*, 2020; Mason, Klapwijk and Smith, 2021). In Brazil, Law 13-123 outlines the lengthy steps that scientists and/or private-sector actors need to take when accessing native biological resources or when applying for import/export authorizations. Similar lengthy procedures are in place in Colombia, a megadiverse country that harbours countless valuable natural enemies but where genetic resources and their derived products are owned by the state (Decree 2811 of 1974, Law 165 of 1994). Challenging procedures and ABS concerns also discourage scientists from embarking upon (or participating in) biological control endeavours in Argentina, India, the Islamic Republic of Iran and Türkiye (Silvestri *et al.*, 2020).

To address roadblocks of this kind, policymakers should be made aware of the broad societal benefits of biological control research and encouraged to set up more enabling ABS policy and risk-management frameworks.

## 4.3 Prospects for policy change and toolbox expansion

To favour the uptake of more environmentally sound pest management, the formulation, roll-out and enforcement of both soft policy measures (e.g. certification schemes and food-safety labelling) and hard policy measures (e.g. conditional financial assistance and regulatory caps) can be considered. Multiple soft policy levers are available to incentivize nature-positive farming and favour the uptake of biological control. These can act as circuit breakers for the often pervasive social and environmental impacts of unsustainable crop protection. The following soft-policy levers are discussed below – certification schemes, crop insurance packages, consumer awareness-raising (food safety, carbon or environmental footprint), labelling and premium pricing.

A range of voluntary sustainability standards and associated certification schemes can aid the uptake of sustainable agriculture. Among 12 major crop standards (organic, fair trade, commodity roundtables) reviewed by Tayleur *et al.* (2017), most include provisions related to on-farm habitat management and reductions in agrochemical pollution. These requirements can potentially aid conservation biological control and create traction for other forms of sustainable crop protection. At present, organic standards probably constitute the largest window of opportunity, as they promote crop production without chemical inputs – thus immediately benefiting resident natural enemies by reducing pesticide-induced mortality. In Costa Rica and Colombia, organic coffee certification has led to important reductions in pesticide use (Blackman and Naranjo, 2012; Ibanez and Blackman, 2016). However, certification schemes need not be limited to organic production or land-based systems. For example, the "Salmon-safe" certification advocates a reduction in agrochemical use within Pacific salmon catchments and introduces management practices aimed at achieving those goals (Tayleur *et al.*, 2017). Similarly, voluntary schemes such as GLOBALG.A.P.[27] could be expanded to include clear goals for the uptake of biological control. Lastly, the "eco-scores" being piloted in 2021–2022 by Foundation Earth and an alliance of Belgian and Spanish entities will inform consumers about the environmental impact of food and drink products, including their carbon footprint and contribution to biodiversity loss. Despite certain shortcomings, labelling and certification can be powerful mechanisms, as they offer a well-established, structured system for tracking farm-level improvements via indicators and auditing procedures (Tayleur *et al.*, 2017). As a low-carbon, biodiversity-friendly tactic, biological control should be a sought-after management solution under many such schemes.

Often, farmers' decisions to deploy curative pest control or prophylactic tactics (e.g. pesticide-coated seeds) are guided by "worst-case" scenarios, moulded by loss aversion and shaped by peer pressure (Heong and Escalada, 1999; Tracey, 2014). Insurance schemes may lower background risks and affect the intensity of pesticide use (Möhring *et al.*, 2020). However, the actual direction of this relation depends on whether pesticides decrease or increase specific risks (as included in the insurance coverage) – which is determined by the crop, farming system and pesticide type (Möhring *et al.*, 2020). In Italy's Veneto region, a specific maize mutual fund has been set up to cover risks related to pesticide misuse and IPM implementation (Furlan *et al.*, 2018). At an annual cost of EUR 3.3 per hectare (i.e. 10 percent of the

[27] https://www.globalgap.org/uk_en/

cost of insecticide seed dressing), this fund primarily covers maize crop damage by wireworms, western corn rootworm, wild fauna and seedling blight. Under the scheme, individual growers are obliged to sign a contract and commit to adopting good agricultural practices, following Directive 128/2009/EC (see above) and implementing guidelines outlined in the region's Annual Crop Bulletin (ibid.). In return, farmers receive up to EUR 1000 per hectare for crop replacement after pest attacks or EUR 250 per hectare for pest-induced crop losses. This approach raises farmers' incomes by cutting unnecessary crop protection expenditures and bolstering natural biological control, while mutual fund revenues can be used for farmer education or to finance habitat-management schemes. Other schemes, such as the Dutch Potatopol insurance established in 1997 to cover risks associated with potato diseases, involve cost and responsibility sharing, and potentially lend themselves to the integration of biological control practices. Lastly, crop insurance schemes can also be used to reward farmers for adopting good farming practices such as the implementation of biological control. By manipulating insurance premiums, particular behaviours can be incentivized (Beckie *et al.*, 2019).

Many actors along the agrifood value chain can (directly, indirectly) contribute to promoting nature-friendly pest management. Policies can mandate traders, food processors and retailers to source produce from organic or regenerative farming operations. Especially for fruit or vegetables that are actively sought for their health benefits, labels that communicate the absence of health-damaging substances could be well received (Wyckhuys *et al.*, 2020a; but see Hartmann *et al.*, 2018). This is, for example, a core element of the business-strategy of the San Francisco-based company Plenty,[28] which uses the presence of "zero pesticides" in vegetables as a sales pitch and a way to target young, health-conscious consumers. In these kinds of clean-farming operations (e.g. in most of Europe's greenhouse sector), augmentative biological control is fully exploited. Along the same lines, other segments of society may respond to labelling that reflects the insect-friendly, honey bee-friendly or environmentally protective nature of food production (Harvey *et al.*, 2020). Carbon labelling is another untapped, yet potentially lucrative, avenue for cutting petroleum-derived inputs and promoting biological control; when food items with large carbon footprints are also made more expensive, a 20 percent shift in consumer purchasing behaviour has been observed (Vanclay *et al.*, 2011).

Premium pricing for certified (and labelled) food items also carries a lot of promise – especially when price signals are tied to information portraying the (human or environmental) health benefits of produce. Globally, people are willing to pay USD 4.6 trillion to avoid premature death or illness caused by pollution, including from agrochemicals (Landrigan *et al.*, 2018). Given their role as endocrine disruptors or in inflicting neurological disorders, pesticides can cause substantial, long-lasting impacts on foetuses and infants (Landrigan *et al.*, 2019). Considering the current absence of warning labels listing pesticide residues in infant formula or baby food, proper labelling and associated premium pricing could be greatly valued by health-conscious parents and parents to be. In some emerging economies such as Viet Nam, consumers are even willing to pay 70 percent more for a certified pesticide-free food basket (Larousse *et al.*, 2019). These schemes could benefit farmers who implement biological control and also generate revenue for educational campaigns, awareness-raising, subsidy schemes, etc.

Any credible scheme to promote agroecological crop protection needs to include a robust educational component, targeting consumers and a range of other value-chain actors. Food safety and ethical self-identity (i.e. individuals' perception of themselves) are prime predictors of consumer attitudes and consumption choices, for example when faced with organic farm produce (Michaelidou and Hassan, 2008). Policies need to be deployed to ensure consumers are informed about the health hazards of pesticide-tainted produce, the existence of dietary alternatives and means of accessing them, and mitigation options within farmers' immediate reach (Poore and Nemecek, 2018; Wyckhuys *et al.*, 2020a). Similarly, by generating and communicating science-based information about classical biological control, a legislative environment can be created in which ecological risks of non-native biological control agents are not overly inflated (Barratt *et al.*, 2018; Catton, 2021). Government agencies, as custodians of public interest science, can facilitate transparent, participatory decision-making by adopting appropriate principles of public engagement and ethics (Sheppard *et al.*, 2019). Deliberative multicriteria evaluation (DMCE) platforms can allow for three-way communication of biological control risks between scientists, stakeholders and legislators (Liu *et al.*, 2011).

Farmers' pest-management decisions generate externalities at broad spatial scales, for example leading to surface-water pollution, food-safety hazards, loss of biodiversity or even the emergence of zoonotic disease (Wyckhuys *et al.*, 2020b; Ratnadass and Deguine, 2021; Oliveira *et al.*, 2021). Measures

[28] https://www.plenty.ag

can potentially be introduced either to incentivize particular behaviours and reward growers for safeguarding ecological resilience ("steward earns") or to penalize them for environmentally disruptive practices such as use of pesticides ("polluter pays") (Porter *et al*., 2017). "Steward earns" incentives can take the form of government subsidies or tax breaks for individual growers but can equally target small and medium-sized enterprises that produce natural enemies, biopesticides or pheromone-based tools. Pairing these two approaches can create much-needed momentum for biological control.

Hard policy levers at legislators' disposal include "command and control" measures such as conditional financial assistance, more stringent maximum residue limits, pesticide taxes and substance bans. At present, only Bhutan and Sri Lanka have opted for a complete ban on synthetic pesticides. Europe's agri-environment schemes provide an example of how financial assistance can be directed towards farmers who deliberately protect farmland biodiversity (and thus safeguard ecosystem services such as natural biological control). The Dutch Delta Plan for Biodiversity Recovery takes this one step further by tying these incentives to tangible (and measurable) gains in wildlife. Stricter maximum residue limit standards are an important (yet underused) means of imparting consumer confidence and even facilitating intercountry trade in farm produce (Drogué and DeMaria, 2012). In the (rejected) 2021 legislative referendum "For a Switzerland without artificial pesticides", residue levels would have served as means of verifying that no pesticide-tainted foodstuffs were imported into the country. These kinds of measures help ensure food safety, lower agrochemical pollution and can be used to promote biological control across agricultural trade partners. The WTO SPS (sanitary and phytosanitary) system can potentially be used to ensure that such trade-related schemes are properly implemented by exporter countries.

Economic instruments such as differentiated taxation schemes for health-degrading pesticides have considerable potential, yet rarely feature in countries' policy mixes (Finger *et al*., 2017). Their success hinges on effective communication of spillover benefits and ultimate policy goals, redistribution of tax revenues for agriculture-related spending and training farmers on pest prevention and non-chemical control methods, for example through tailored technical backstopping and the generation of so-called actionable knowledge (Geertsema *et al*., 2016; Finger *et al*., 2017). Rather than an *ad valorem* or per-unit tax, pesticides are preferably taxed based upon their riskiness and ecological selectivity (Jepson *et al*., 2020). A smart policy package can thereby couple a progressive, risk-based pesticide tax with tailored subsidies that lower the price of biopesticides and BCAs (Grovermann *et al*., 2017). This has certain advantages over single-substance bans, which routinely trigger stiff industry lobbying, can drive a wedge between environmentalists and farmers and ultimately obstruct input substitution and redesign phases within farm-scape transformation (Vanbergen *et al*., 2020).

## 4.4 Opportunities to position biological control within particular legislative frameworks

Plant-health policies have important interdependencies with other policy targets and instruments, for example those related to water and sanitation, food safety, biodiversity protection, decarbonization, human rights and human health, and these should be accounted for in policy design. A non-exhaustive list of opportunities to infuse different legislative frameworks with measures to promote biological control and agroecological crop protection is provided below.

### 4.4.1. Overarching science, technology and innovation policy

Science, technology and innovation (STI) policies are key to achieving the UN Sustainable Development Goals (SDGs), and appropriate STI policy frameworks and governance forms still need to be developed and implemented in many parts of the world. Inadequate policies and unwieldy regulatory environments at national levels can be significant constraints to the pursuit of more sustainable forms of crop protection, (Barratt *et al*., 2018; Bakker *et al*., 2020). The legislative environment can impede the development of biological control technologies, prevent in-country registration of non-chemical alternatives or obstruct their roll-out at farm level. A first element of concern is how crop protection science is often assigned far lower priority than other STI fields, for example in the Asia–Pacific region (Wyckhuys and GC, in press). This is further compounded by a dramatic decline in the number of biological control research positions in academic institutions in the United States of America and Australia (Barratt *et al*., 2018; Messing and Brodeur, 2018; Carlisle *et al*., 2019). In California, this decline in institutional capacity relates to 1) reconfigurations of university research priorities, 2) transformation and privatization of the life sciences and 3) dwindling interest in biological control among activist groups (Warner *et al*., 2011). Hence, ensuring that biological control (and sustainable crop protection in general) is addressed in national

STI policies and university curricula is a necessary step towards realizing its potential. This also involves providing fellowships in biological control at all levels, sponsoring traineeships or participation in workshops and conferences, and facilitating basic research, for example in taxonomy (Hoeschle-Zeledon *et al.*, 2013).

Though biological-control science has generated a wealth of knowledge over recent decades, this science-derived knowledge only sporadically leads to tangible outcomes, such as improved farmer practices, biodiversity recovery or higher farmer incomes (Wyckhuys *et al.*, 2018c; Gonzalez-Chang *et al.*, 2020). Ecosystem-service science clearly needs to become more applicable and accessible to decision-makers (Mandle *et al.*, 2020). National regulatory entities can be guided in their development of suitable policies, for example by systematically contrasting chemical and non-chemical crop-protection measures that are available to farmers (Veres *et al.*, 2020) or by visualizing the extent to which biological-control science has yielded on-the-ground social–ecological outcomes. A web-based, interactive spiral approach can be used to map the progress that has been made in harnessing biodiversity for crop protection within specific geographies or for specific combinations of crops and pests (Bioprotection, 2022). Use of this approach has revealed that farm-level management protocols are often formulated without even basic insights into pest or natural-enemy ecology (FAO, 2022a). It can help regulators to strategize science and avoid knowledge-deficient initiatives.

### 4.4.2. Agrifood value chain stakeholder education

Although farmers' ecological knowledge is a key determinant of the type, intensity and ecological impact of crop protection (Wyckhuys *et al.*, 2019a), implementing farm-level policies is challenging. While farmers' decision-making is pivotal to the diffusion of biological control, regulators need to recognize that there are multiple other actors in the agrifood value chain (Möhring *et al.*, 2020). A more holistic, participatory approach and the mobilization of sector-wide support are thus central to effective transformation of global pest management. As exemplified for nitrogen reduction (Kanter *et al.*, 2020), farm-level management practices can be indirectly improved by engaging, for example, input suppliers, farm advisors, processors, traders, retailers, wastewater managers and consumers. Across the globe, underfunded government extension systems not only fail to provide farmers with sufficient support on IPM and biological control (Rola and Pingali, 1993; Pretty and Bharucha, 2015) but also often suffer from sectoral bureaucracies and have anaemic levels of capacity (e.g. Teoh and Ooi, 1986; Deguine *et al.*, 2021). Meanwhile, crop protection salespersons and industry-funded crop advisors are thought to outnumber government extension personnel by three to one in the Philippines and ten to one in Nepal (Wyckhuys and GC, in press). Even for farmers who independently wish to seek biological control solutions through the internet, options are limited in countries outside western Europe and North America (Wyckhuys *et al.*, 2019b). This can be resolved by abandoning the traditional "research-push" model and paternalistic, top-down extension schemes and embracing participatory approaches.

A lot can also be gained by adopting an innovation-systems perspective and pursuing systemic facilitation or so-called "innovation brokering" (Klerkx *et al.*, 2012). Strengthening stakeholders' ecological knowledge base is key to the success of initiatives of this kind. One way of doing so is through FFS-style, discovery-based learning (aimed primarily at farmers). In several countries, paper-based or digital pictorial guides of natural enemies have been distributed among cereal or tropical-fruit farmers (e.g. under Canada's Field Heroes programme). Digital portals such as Access Agriculture[29] or Eco-Agtube[30] provide access to farmer-to-farmer educational videos that aim to transfer biological control concepts and principles. A second way to educate and engage other actors in the agrifood value chain is by accounting for the true (planetary health) cost of food production (Baker *et al.*, 2020). This involves holistically evaluating the costs and benefits of different food systems (and, indirectly, pest management regimes) and gauging their impacts on human and environmental health. This can enable transformative change at policy, product, organizational, farm and investment levels. One way to operationalize the approach is by using the traffic-light "eco-score" coding system that is currently being piloted by entities in the United Kingdom and elsewhere in Europe. The former already engages food company giants such as Nestlé and provides unmatched opportunities to educate consumers and retailers on biological control.

### 4.4.3. Human health and food safety

Certain crop-protection practices (e.g. overreliance on synthetic pesticides) can have immediate impacts on human health. This occurs via the direct effects of accidental poisoning or occupational exposure

[29] https://www.accessagriculture.org/
[30] https://www.ecoagtube.org/

of farm workers, but the most common exposure pathway is through dietary intake of synthetic pesticide residues in harvested produce and drinking water (Fantke and Jolliet, 2016). At present, between a quarter and a half of fruit and vegetable samples have residues that exceed maximum residue levels (MRLs) in multiple countries (Skretteberg *et al.*, 2015; Bhandari *et al.*, 2019). Since 1963, FAO and the World Health Organization (WHO) have set up several committees to tackle pesticide-related health risks. Across the globe, countries tend to adopt or adapt MRLs that are proposed in the joint FAO–WHO Codex Alimentarius for certain compounds and food items, though these imperfectly capture life-long health risks (Wyckhuys *et al.*, 2020a). Three non-exclusive ways of facilitating the adoption of biological control are: 1) defining and legally enforcing strict MRL standards; 2) tightening existing MRLs in a differential manner, for example based upon the riskiness and ecological selectivity of pesticidal compounds (Jepson *et al.*, 2020); and 3) developing compound-specific restrictions based on the availability and "implementation readiness" of non-chemical alternatives (Wyckhuys *et al.*, 2020b).

Opportunities also exist to upscale biological control through water-related policies and legislation. In Viet Nam, for example, synthetic pesticide pollution (e.g. in paddy rice systems) is so extensive that it degrades potable water resources (Pham *et al.*, 2013). Among the detected active ingredients, Viet Nam's National Technical Regulation on Surface Water Quality (QCVN 08, 2008/BTNMT) considers only one synthetic pesticide compound, endosulfan (ibid.). Water-quality certification should be based on multicompound screening and needs to go hand-in-hand with policies that aim to educate stakeholders about health risks and the protection of water sources (e.g. through biological control) (Migheli, 2017). Inserting risk mitigation into existing legislative and policy frameworks can help attain drinking-water and food-safety regulatory compliance both in Viet Nam and across the world (Wee and Aris, 2017).

### 4.4.4. Climate change

Global agrifood production has a large carbon footprint, currently accounting for more than 20 percent of the world's GHG emissions (Woods *et al.*, 2010; Crippa *et al.*, 2021), and the manufacture, distribution and field-level application of synthetic pesticides annually generates 20 million tonnes of carbon equivalent (range 6.4 to 37.2 million tonnes) (Wyckhuys *et al.*, 2022). Agriculture in general, and crop protection specifically, thus need energy-efficiency and decarbonization policies that pursue GHG reductions via technological change and/or altered consumer behaviour (Crippa *et al.*, 2021). In the United States of America, fossil-fuel consumption in the agriculture sector could be substantially reduced through technological innovations such as crop rotations, cover crops and mechanical cultivation to curb synthetic herbicide use (Pimentel *et al.*, 2008; Springmann *et al.*, 2018; Clark *et al.*, 2020). Some of these tactics directly benefit (natural) biological control and thus lower the need for curative, pesticide-based interventions – although their (indirect, biodiversity-mediated) carbon benefits are often disregarded. Meanwhile, classical and augmentative biological control replace chemical inputs and thus directly reduce the carbon footprint of agriculture.

A suite of options for decarbonizing agriculture are available, ranging from heightened efficiencies, through substitution of energy-intensive inputs to more systemic changes such as overarching redesign of the farming system (Pretty *et al.*, 2018).One example of the latter is climate-smart agriculture (CSA), which aims to enhance food and nutritional security, bolster resilience to pest shocks (e.g. by harnessing biodiversity for crop protection), lower GHG emissions and sequester carbon (Vanbergen *et al.*, 2020). By inserting CSA into countries' climate change mitigation strategies and carefully defining its goals, momentum can be generated for low-carbon solutions such as biological control. In Australia, arrangements are being trialled under the Emissions Reduction Fund to reward farmers for curbing carbon emissions while also improving on-farm biodiversity (Standish and Prober, 2020). Farmers who establish or restore native vegetation will receive an alternative income stream to help drought-proof their businesses, in addition to earnings derived from carbon abatement. Both vegetation and decarbonization projects can enhance natural biological control, and this could possibly be accounted for when refining farmer reward schemes. Conversely, carbon markets increasingly help finance nature-based solutions and voluntary offset schemes prove lucrative in the aviation industry (Gössling *et al.*, 2007; Girardin *et al.*, 2021).

Efficient and credible GHG offsets that adhere to standards can potentially incentivize farmers to move towards more climate-friendly production modes, including low- or no-pesticide farming schemes (Niles *et al.*, 2019). California's cap-and-trade programme includes two protocols aimed at agriculture, but none cover emissions related to crop protection. In the United States of America, the Biden administration is contemplating the establishment of a carbon bank where farmers could sell carbon credits to polluting industries and enterprises. Biological control also provides options beyond emission mitigation; inserting it into global programmes such the United Nations Framework Convention on Climate Change's REDD+ (reducing emissions from deforestation and forest degradation in developing countries, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks) can allow biodiversity-driven pest or disease management to be enhanced through ecological infrastructure (e.g. hedgerows and forest plots) while simultaneously increasing carbon capture.

### 4.4.5. Biodiversity recovery

The global economy is dependent on and embedded in nature (Dasgupta, 2021). Yet, over the past five decades, biodiversity and nature's ecosystem services have been in precipitous decline worldwide (Díaz *et al.*, 2019). Agriculture is a major contributor to global biodiversity loss, with crop-protection practices often considered to be acutely unfavourable to nature. To address these problems, a mitigation hierarchy has been proposed that can be applied on a voluntary or regulatory basis across sectors, actors and geographies and serve as a core principle underlying biodiversity policy (Milner-Gulland *et al.*, 2021). The framework lays out objectively verifiable, measurable targets (e.g. "net biodiversity gain") to assess project outcomes or identify biodiversity offsets through which project impacts can be compensated. Setting measurable targets of this kind and conducting routine biodiversity monitoring, potentially in parallel with the tracking of chemical pollutants, can operationalize outcome-based stakeholder incentives. The latter are core components of the Dutch Delta Plan for Biodiversity Recovery – a programme aligned with CBD goals and the Aichi Targets that involves farmers and other non-state actors (Eiselin, Simons and Verwer, 2020). Financial schemes such as green subsidies and green deals are mobilized to reward land users (e.g. land-managers, farmers and private individuals) for large scale "nature creation" or small-scale initiatives aimed at promoting the recovery of insect and farmland bird populations, for example by replacing pesticides with biological control. Unambiguous measurement of actors' performance and how those add up to real biodiversity gains enables payments for ecosystem services. To ensure that biological control is actively considered as a biodiversity-friendly farming solution, work is needed to catalyse awareness among decision-makers, to educate actors along the agrifood value chain, to explicitly illuminate biological control's biodiversity benefits and to engage conservationists. High-profile initiatives, such as avoidance of tropical forest loss or restoration of native fauna through biological control, need to be widely showcased (e.g. Van Driesche *et al.*, 2010; Wyckhuys *et al.*, 2019c).

### 4.4.6. Human rights and worker protection

In many parts of the world, statutes and regulations are in place to protect people's rights to life, health and livelihoods (Dinham and Malik, 2003). In 2017, this issue was brought to the fore in the reports of the Special Rapporteur on the Right to Food, Hilal Elver, and the Special Rapporteur on Toxics, Baskut Tuncak, to the UN Human Rights Council. Aside from underlining how pesticides are a global human rights concern, emphasis was placed on the need to implement harmonized, stringent regulations on pesticide production, sale and use. Both rapporteurs also pointed out how non-chemical alternatives such as agroecology (and biological control, as one of its components) can adequately feed and nourish the world's population, while safeguarding the rights of future generations to health. Reports presented in 2022 by the Special Rapporteur on the Environment, David R. Boyd, refer to the environmental impacts of food systems, including the impacts of toxic chemicals and pollution, on human rights (United Nations, 2022a,b). In July 2022, the United Nations General Assembly recognized the right to a clean, healthy and sustainable environment as a human right (United Nations, 2022c).

For decades, the UN International Labour Organization has highlighted the ways in which workers continue to be disproportionally exposed to chemicals, including synthetic pesticides (ILO, 1993, 2021). While in the past emphasis was placed on encouraging the safe and responsible use of such products, a recent report also underlines the need to promote IPM and up-scale farmers' use of low-risk biological alternatives (ILO, 2021). International legal instruments for the protection of workers' health can counteract country-level initiatives that aim to relax or reverse pesticide-use restrictions (Mosmann, Albuquerque and Barbieri, 2019). As opposed to relaxing pesticide legislation, countries should instead pursue the worker safety benefits that accrue from facilitating the availability of biological control.

### 4.4.7. Post-COVID-19 recovery

Since early 2020, the COVID-19 pandemic has spotlighted the dangers associated with novel zoonotic diseases. Irrespective of the exact origins of COVID-19, zoonotic and vector-borne diseases inflict substantial levels of human mortality and morbidity worldwide, and their increased incidence is directly tied to biodiversity loss and ecosystem degradation (Morand and Lajaunie, 2021). Moreover, the indiscriminate use of insecticides in the world's farming system impacts the fitness and immune response of bats (globally important virus reservoir hosts) and thereby raises the likelihood of animal–human transmission (Torquetti, Guimarães and Soto-Blanco, 2020; Oliveira *et al.*, 2021). Yet, while pesticide-use reduction may have immediate spinoffs in terms of preventing future zoonotic pandemics, the mitigation role of biological control and other biodiversity-friendly farming practices is regularly disregarded (Petrovan *et al.*, 2021).

### 4.4.8. World trade

Given the globe-spanning trade in agrifood produce, countries are mutually dependent on biodiversity-based ecosystem services such as biological control (Silva *et al.*, 2021). Ever more often, local changes to agricultural systems are shaped by policies and phenomena beyond a country's national borders; consumption patterns in developed countries increasingly drive unsustainable crop management in the Global South (O'Bannon *et al.*, 2014; Hoang and Kanemoto, 2021). Conversely, pest-induced crop losses (e.g. due to a loss in natural biological control or the appearance of invasive pests) can lead to trade shocks and price overshooting in traded agricultural commodities (Wyckhuys *et al.*, 2018b). As such, food prices can serve as feedback signals of the ecological resilience of farming systems.

Given the ways in which it directly benefits resilience, agroenterprises stand to gain if they can implement biological control while eliminating environmentally damaging practices such as unguided pesticide use. In the same vein, resilience measures or biological control indices can inform the decision-making of financial actors, such as banks or investors, and stakeholders in the food value chain (Galaz *et al.*, 2015; Sukhdev, 2018). They can also steer national and intercountry ecological fiscal transfers and thereby further incentivize ecological restoration (Busch *et al.*, 2021). Moreover, by coupling such metrics with existing price-stabilization mechanisms, trade can act as a "restorative" force and indirectly boost the uptake of biological control (Martinez-Melendez and Bennett, 2016; Pace and Gephart, 2017). As such, transnational corporations and Western agrifood enterprises have a stake in the preservation or active restoration of healthy and biologically rich agroecosystems (Folke *et al.*, 2019). Biological control could be a central element within such initiatives.

## 4.5 Access and benefit-sharing regulations

The CBD has three main objectives: 1) the conservation of biological diversity; 2) the sustainable use of the components of biodiversity; and 3) the fair and equitable sharing of the benefits arising out of the utilization of genetic resources. The Nagoya Protocol provides a legally binding framework for the implementation of the third of these objectives.

"Utilization of genetic resources" in the Nagoya Protocol means to conduct research and development on the genetic and/or biochemical composition of genetic resources, including through the application of biotechnology as defined in Article 2 of the Convention. The CBD and the Nagoya Protocol empower ratifying countries (parties) to regulate access to genetic resources for their utilization under their national jurisdictions (CBD Article 15.1 and Nagoya Protocol Article 6.1). Subject to relevant domestic legislation, access to a country's genetic resources requires prior informed consent (CBD Article 15.5 and Nagoya Protocol Article 6.1) and mutually agreed terms (CBD Article 15.4 and Nagoya Protocol Article 5.1). Implementation of ABS regulations can have direct impact on access to BCAs and their use.

National ABS measures usually require a formal agreement between the competent authority and recipients of BCAs who wish to use them for research and development. Biological control, in particular classical and augmentative practices, can be negatively affected by these requirements (van Lenteren, 2021). Historically, there has been a community of practice based on the principle of free multilateral exchange of BCAs rather than bilateral ABS agreements (Cock *et al.*, 2009). The unconditional exchange of BCAs among relevant stakeholders has been common practice for many years. One reason for this may be that BCAs are for the most part not developed into commercial products, and even if they are, as they are not subject to intellectual property protection, provider countries do not need to worry about other countries or corporations preventing them from developing and using the BCAs (Cock *et al.*, 2010; van Lenteren, 2021; Mason *et al.*, 2021).

The features of biological control include the following: a) its widespread use in both developing and developed countries and the fact that countries are both providers and users of BCAs; b) the fact that BCAs are not patented and that all information associated with classical BCAs is put into the public domain; c) the fact that many BCAs are exchanged but have little recoverable monetary value; and d) the fact that biological control creates and sustains societal benefits for all, including food security, food safety, human health (by reducing pesticide use), control of invasive alien species, protection of biodiversity and maintenance of ecosystem services (Cock *et al.*, 2009).

The adoption of the Nagoya Protocol and non-strategic and poorly planned ABS national regimes have delayed or prevented the exploration of natural enemies for classical and augmentative biological control research and practice (Cock *et al.*, 2009; Smith *et al.*, 2018; Silvestri *et al.*, 2020). Obstacles commonly encountered by research entomologists and biological control practitioners have included the following: a) complicated procedures for accessing biological control genetic resources for research; b) complicated procedures for obtaining prior informed consent or mutually agreed terms; c) poor institutional capabilities for facilitating ABS compliance; and d) rapid turnover of provincial, state or national focal points, competent authorities and staff dealing with the utilization and export of microbial and invertebrate BCAs (Silvestri *et al.*, 2020). Difficulties in meeting countries' national ABS requirements have led to long delays in BCA releases, reduction or loss of funding, changes of provider country and even cancellation of projects (Silvestri *et al.*, 2020).

Another common drawback is that different countries have different criteria for determining which uses of genetic resources require benefit-sharing through mutually agreed terms (Smith *et al.*, 2018). There is a need to clearly identify which activities related to microbial and invertebrate genetic resources are considered "utilization" and which are not. It is noteworthy that the taxonomic identification of microbial and invertebrate BCAs and the evaluation of their host specificity and assessment of their effectiveness are not within the scope of the regulations in many countries, for example, EU Regulation No 511/2014[31] (Smith *et al.*, 2018) and Argentina Res. 410/2019.[32]

In the EU, regulation of access to genetic resources is a matter for individual states, and while most EU countries do not restrict the sharing of genetic resources with Member or non-Member countries (Smith *et al.*, 2018), France and Spain, for instance, have put legislation in place to control access.[33] Many countries elsewhere in the world have stricter export requirements, and many companies, research institutions and NGOs have had difficulty importing novel materials from them or have stopped trying altogether (Nijar *et al.*, 2017; Neumann *et al.*, 2018; Avilés-Polanco *et al.*, 2019; Heinrich *et al.*, 2020). This has been referred to as an ironic backfire of the Nagoya Protocol, as it reduces commercial and scientific investment in "source" regions, such as the biodiverse and less economically developed global South (Deplazes-Zemp *et al.*, 2018). There have been calls to relax the requirements of the Nagoya Protocol, particularly for non-commercial research purposes (Cock *et al.*, 2010; van Lenteren *et al.*, 2018), and these have resulted in attempts to facilitate the ABS process. The intergovernmental organization CABI has established country-specific guidelines for its staff on how to work within the Nagoya Protocol (Smith *et al.*, 2018). This example may provide a template for the development of streamlined guidelines by other bodies. Other suggestions have included the creation of open-source databases (e.g. for genetic data) that comply with ABS practices, and the use of decision-making frameworks (Schindel *et al.*, 2015; Mason *et al.*, 2018; Smith *et al.*, 2018).

Classical biological control has been recognized by the CBD (CBD/COP/DEC/XIII/13) as a proven method for managing invasive alien species. To deliver and sustain country, regional and global benefits from biological control, it is important to stress the relevance of biological control as a public good. The Nagoya Protocol encourages its parties to create conditions that promote access to genetic resources for non-commercial purposes, such as classical biological control, through simplified measures, and to consider the importance of GRFA, which include BCA genetic resources, and their special role for food security (Nagoya Protocol Article 8a and Article 8c). Free multilateral exchange through the global network of biological control professionals deserves special consideration with respect to ABS (Cock *et al.*, 2009). It has been recommended that government authorities adopt simplified measures for access to and exchange of BCAs or consider exempting activities from the scope of ABS regimes if they support the public good or protect the environment (Cock *et al.*, 2009; Silvestri *et al.*, 2020).

The emergence and expansion of "digital sequence information" (DSI) has created a significant additional challenge with respect to the use of genetic resources, including BCA genetic resources. The rise of genetic sequence data in the public

[31] Regulation (EU) No 511/2014 of the European Parliament and of the Council of 16 April 2014 on compliance measures for users from the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization in the Union Text with EEA relevance. https://eur-lex.europa.eu/eli/reg/2014/511/oj

[32] Secretaría General. Secretaría de Gobierno de Ambiente y Desarrollo Sustentable. Resolución 410/2019. RESOL-2019-410-APN-SGAYDS#SGP. Ciudad de Buenos Aires, 22/10/2019. https://www.argentina.gob.ar/normativa/nacional/resoluci%C3%B3n-410-2019-330606

[33] See https://absch.cbd.int/en/ for further information on this legislation.

domain has complicated the already difficult issue of traceability in negotiations over benefit-sharing. Some countries have specific ABS rules related to DSI, some do not, and some decouple DSI from the genetic resource. As a consequence, DSI has become a challenging topic of discussion, first and foremost in the scope of the CBD and the Nagoya Protocol[34] but also in many other international fora, for example the World Health Organization's Pandemic Influenza Preparedness Framework, the CGIAR, the United Nations Convention on the Law of the Sea (with regard to addressing governance gaps in relation to the use of marine biological resources in areas beyond national jurisdiction), the Commission and the International Treaty on Plant Genetic Resources for Food and Agriculture.

Taxonomic identification of target pests and of microbial and invertebrate BCAs or genetic material by means of morphological or molecular analyses constitutes a crucial step in any biological control project. The Commission recognizes that there is a need to address the innovation opportunities that DSI offers, the challenges related to capacity to access and make use of DSI, and the implications of DSI for the conservation and sustainable use of GRFA and for the sharing of benefits derived from GRFA (FAO, 2019a).

Communication and awareness-raising on ABS measures among potential providers, holders and users of BCA genetic resources is essential. The establishment, in 2008, of the International Organization on Biological Control Global Commission on Access and Benefit-Sharing (IOBC-GCABS)[35] was an important development in this regard. Examples of the IOBC-GCABS's linkages with international partners have included its authorship of Commission Background Study Paper No. 47, *The use and exchange of biological control agents for food and agriculture* (Cock *et al.*, 2009), which summarizes the situation with respect to the use and exchange of BCAs and the potential implications of ABS measures. In addition, the IOBC-GCABS wrote a forum article taking a more political stance and an advocacy role on behalf of the IOBC community (Cock *et al.*, 2010). Over recent years, the IOBC-GCABS has been very active in presenting conference papers (Gourlay, Shaw Cock, 2013; Barratt *et al.*, 2017; Silvestri *et al.*, 2019; Colmenarez *et al.*, 2021) and organizing sessions and workshops during international scientific conferences (XIII International Symposium on Biological Control of Weeds Proceedings 2011 [Wu *et al.*, 2013]; 5th International Symposium on Biological Control of Arthropods Proceedings 2017 [Mason, Gillespie and Vincent, 2017]; XV International Symposium on Biological Control of Weeds Proceedings 2018 [Hinz *et al.*, 2019]; Second International Congress of Biological Control 2021) to inform the biological control community of the importance of ABS in this field. The IOBC-GCABS has also formulated a code of best practices for the use and exchange of invertebrate BCA genetic resources relevant for food and agriculture (Mason *et al.*, 2018). The best practices include a) collaboration to facilitate information exchange about what invertebrate BCAs are available and where they can be obtained, b) knowledge sharing through freely available databases that document successes and failures, c) cooperative research to develop capacity in source countries, d) transfer of production technology to provide opportunities for small-scale economic activity (Barratt *et al.*, 2017; Mason *et al.*, 2018) and e) a model concept agreement for scientific research and non-commercial purposes, applicable in countries where ABS regulations exist and in those where they do not (Mason *et al.*, 2018).

Given that classical BCAs are provided as a free-of-charge public good contributions to all countries and the net profit margins to companies selling BCAs commercially are small (3 to 5 percent of revenues: Cock *et al.*, 2009), where ABS laws require mutually agreed terms to be negotiated, biological control researchers and practitioners should also consider non-monetary benefits. Non-monetary benefits can be provided by closely involving local entities (universities, research institutes, regulatory authorities, indigenous peoples and local communities) in the provider countries in the scientific aspects of the biological control projects, including participation in field exploration, exchange visits, training of students and scientists, joint authorship of scientific publications and joint submission of research proposals. To ensure transparency and nurture trust, it is also important to provide regular updates about the progress of biological control projects to, for example, the regulatory agencies, museums and universities of the country or province of origin of the genetic resources, and to invite provincial/national regulators to field release events for BCAs in the recipient country (Coutinot *et al.*, 2013).

Planned future actions of the IOBC–GCABS include the use of a questionnaire to gather information on the challenges biological control researchers and practitioners face when accessing BCAs and identify whether challenges differ depending on whether the BCAs are intended for release into nature or for development of a commercial product, and the provision of guidance on the development of

[34] See https://www.cbd.int/dsi-gr for further information on the CBD's work on DSI.
[35] https://www.iobc-global.org/global_comm_bc_access_benefit_sharing.html

recommendations on access and use of BCA genetic resources for governments and the biological control community. The IOBC–GCABS is also drafting a document describing best practices for microbial BCAs. This will build on existing practices, such as the Micro-Organisms Sustainable Use and Access Regulation International Code of Conduct (MOSAICC) developed by the Belgian Coordinated Collections of Micro-organisms consortium.[36] This code of conduct strives to increase awareness of the potential

Education and training provide another opportunity to raise awareness of ABS measures. Since 2017, the Faculty of Exact and Natural Sciences of the University of Buenos Aires, in collaboration with the NGO the Foundation for the Study of Invasive Species, offers a postgraduate course that covers ABS measures in relation to biological control of invasive pests.[37]

[36] https://bccm.belspo.be/projects/mosaicc

[37] https://www.ege.fcen.uba.ar/academico/posgrado/cursos-de-posgrado/

# Chapter 5. Microbial biostimulants

## 5.1 Background and state of use

### 5.1.1. Definition and description

Biostimulants have been defined as "fertilising product[s] the function of which is to stimulate plant nutrition processes independently of the product's nutrient content with the sole aim of improving one or more of the following characteristics of the plant or the plant rhizosphere: (a) nutrient use efficiency, (b) tolerance to abiotic stress, (c) quality traits, or (d) availability of confined nutrients in the soil or rhizosphere" (European Union, 2019). In the context of changing consumer preferences for organic and other sustainably produced foods and changes in laws and regulations related to the use of synthetic fertilizers and pesticides, biostimulants are interesting options as sustainable alternatives to synthetic inputs and as means of contributing to the sustainable intensification of crop production. A number of bacteria and fungi act as biostimulants, enhancing plant growth and eliciting plants' natural defences against pests and diseases (Pineda *et al.*, 2010; Vidal and Jaber, 2015; Galambos *et al.*, 2021).

### 5.1.2. Species used and production systems where used

Biostimulants are used in various types of production system, including low-input and high-input systems, organic and conventional systems, agroecological systems, industrial systems and integrated systems. They are used in open fields and greenhouses, and for a variety of crops, including fruit trees and other trees, berries, grapes, vegetables, ornamentals, cereals, turf and pasture grass (Basile *et al.*, 2020; Rouphael *et al.*, 2017; Rouphael *et al.*, 2018; Rouphael *et al.*, 2020a; Rouphael and Colla, 2020).

Two categories of biostimulants exist: microbial (in particular plant growth-promoting rhizobacteria [PGPR] and arbuscular mycorrhizal fungi [AMF]) and non-microbial (for example humic substances, seaweed extracts, chitosan-based products and silicon) (Figure 3). The focus here is on microbial biostimulants.

#### Plant growth-promoting rhizobacteria

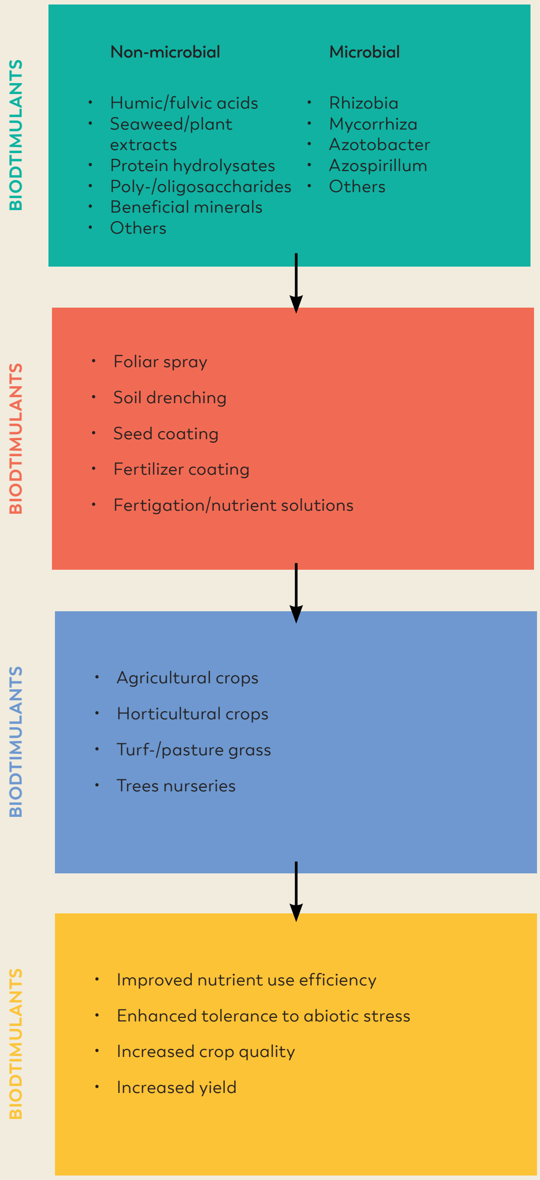
Plant growth-promoting biostimulants occur in the Rhizobacteria phyla (Actinobacteria, Proteobacteria and Firmicutes) and include strains belonging to genera *Bacillus, Pseudomonas, Azospirillum, Azotobacter, Alcaligens, Arthobacter, Agrobacterium, Burkholderia, Comamonas, Pantoea, Rhizobium, Serratia* and *Variovorax* (Ruzzi and Aroca, 2015). Nitrogen-fixing bacteria (*Rhizobium*) are beneficial to legumes, as nitrogen is an important and often limited nutrient, especially in poor soils. Other nitrogen-fixing bacterial species associate with other important crop plants, including cereals, for example *Herbaspirillum seropedicae* with rice plants.

According to Backer *et al.* (2018), research has demonstrated that inoculating plants with PGPR can be an effective means of stimulating their growth and improving their tolerance of the abiotic stresses likely to become more frequent with changing climatic conditions (e.g. drought, heat and salinity). Examples of the effects of PGPR application in vegetable crops, fruit crops and flower and ornamental plants are presented in Tables 1 to 3 of Ruzzi and Aroca (2015). However, understanding of the mechanisms of action of PGPR, for example of factors such as root exudates and intermicrobial signalling, is still relatively limited (Rouphael *et al.*, eds, 2020b). Gaining a more complete understanding of the interactions between plants and PGPR will make it easier to exploit these relationships (Backer *et al.*, 2018).

#### Arbuscular mycorrhizal fungi

AMF establish mutualistic relationships with 74 percent of terrestrial plant species (Van Der Heijden *et al.*, 2015; Spatafora *et al.*, 2016 cited in Rouphael *et al.*, 2020b) based on bidirectional transfer of nutrients (Smith and Read, 2008). Host plants provide physical support and a favourable metabolic framework for the AMF, and the AMF receive carbon fixed by the host plant's photosynthesis in exchange for mineral nutrients that they provide to the plant via the fungal mycelial network (Smith and Read, 2008). Crops associated with AMF include cereals, fruit trees, vegetables

**Figure 3. Application of biostimulant products to crop plants and claimed agricultural functions**




*Source*: Rouphael, Y., du Jardin, P., Brown, P., De Pascale, S. & Colla, G., eds. 2020. *Biostimulants for sustainable crop production*. London, Burleigh Dodds Science Publishing. Reproduced with permission.

and ornamentals. Commercial AMF products are used in gardening and landscaping, horticulture and forestry. Examples of effects of inoculation with AMF species on the agronomical, physiological and biochemical performance of various horticultural crops in conditions of drought, salinity, nutrient deficiency, presence of heavy metals, and adverse soil pH conditions are presented in Tables 1 to 5 of Rouphael *et al.* (2015).

As of May 2021, 342 species of AMF had been described.[38] Only a small proportion of AMF are exploited as biostimulants, with the main species used being *Rhizophagus irregularis* and *Funnelliformis mosseae*, and to a lesser extent *Glomus etunicatum* and *G. fasciculatum* (Rouphael *et al.*, 2020b). There has been a lot of research on the symbiotic interactions between AMF and crop plants. Interest is increasing in interactions among AMF species and strain ecotypes, other components of the soil biota, environmental variables, farm management and crop genotypes (e.g. Gryndler *et al.*, 2018; Ryan and Graham, 2018).

### 5.1.3. Extent of adoption, economic value and differences between regions

The overall biostimulant market, including microbial and non-microbial products, was estimated at USD 2.6 billion in 2019 and is projected to reach USD 4.9 billion by 2025 (Markets and Markets, 2019), with thousands of products available on the market (du Jardin, 2015; Yakhin *et al.*, 2017).

Bonini *et al.* (2020) identify the following main drivers of market growth for biostimulants (microbial and non-microbial):

- product efficacy (yield increase of approximately 5–15 percent, quality improvement in staple foods and horticultural products, reduction in use of agrochemicals by approximately 10–15 percent);

- innovation (development of new biostimulant products and application strategies, involvement of multinational companies);

- market expansion (increased number of biostimulant-treated crops, including broadacre crops, new roles for plant biostimulants, such as soil and seed applications); and

- sustainability (environmental constraints reducing fertilizer and pesticide input; regulations promoting sustainable agriculture practices).

[38] http://www.amf-phylogeny.com/amphylo_species.html

The world market for bacterial biostimulants is growing (du Jardin, 2015). According to currently available literature, less than 25 percent of commercial biostimulants products are microbial based (Hamid *et al.*, 2021).

The market for AMF is expanding rapidly, with the number of companies in Europe – the dominant region – doubling in the ten years to 2018 (Chen *et al.*, 2018). Twelve percent of the total biostimulants market consists of products based on mycorrhiza (Bitterlich *et al.*, 2020 citing the European Biostimulants Industry Council). Growth in the consumption of organic food (Caradonia *et al.*, 2018) and national and EU regulations that put particular emphasis on promoting sustainable alternatives to traditional chemical fertilizers (Bitterlich *et al.*, 2020) are driving the market in Europe. Over the same period, markets such as China and India in Asia, and Argentina, Brazil, Colombia and Mexico in Latin America, have shown considerable growth in the availability of AMF products (ibid.). The AMF market is dominated by small and medium-sized enterprises; a few large companies, operate mainly from Europe and North America (Chen *et al.*, 2018).

Biostimulants are a very active research field. A term search for "plant biostimulants" resulted in more than 1 000 scientific papers published between 2010 and 2020 (Rouphael and Colla, 2020). A search of the 13 944 000 records held in CAB Direct (see Section 2.1) produced 1 220 hits for "biostimulants", 15 067 hits for "growth stimulants" and 12 239 hits for "biofertilizers".

## 5.2 State of management

### 5.2.1. Breeding, potential use of subspecies and the state of use of management practices

Classical breeding or genetic transformation to obtain AMF with stable, desirable traits are currently impossible given the specific characteristics of fungal genetic systems (Chen *et al.*, 2018). Microbiome engineering based on **synthetic biology** allows laboratory selection of microbes according to their ability to colonize plants and promote plant growth (Ke, Wang and Yoshikuni 2021). Such microbes could potentially be delivered to specific plant species and locations (e.g. roots or leaves) at different growth and developmental stages under various environmental conditions, and diverse PGP traits could be consolidated in the engineered microbiomes (ibid.).

### 5.2.2. State of conservation

As noted in Section 3.3, *ex situ* conservation of microorganisms is done through private collections and public-service collections, such as those affiliated with the WFCC. As in the case of microbial BCAs, the conservation of biostimulant strains is incomplete, and hence they are not always available for further study and use. Those currently being used by the private sector are maintained, but beyond this conservation is poorly addressed.

Like BCAs, biostimulants can be found among the holdings of publicly available microbial culture collections. However, they are not properly labelled or characterized and information on them is not easily found. As mentioned in Section 3.3, the collections listed on the WDCM contain close to 3.3 million microbial strains. Of 148 000 species of fungi described, only 25 611 species (just over 17 percent) are cultured and publicly available (Paton *et al.*, 2020). There are a few collections that clearly state they hold microorganisms considered to be biostimulants, but overall the data on the conservation of microbial biostimulants are scattered and not accessible.

## 5.3 Policies and instruments

European Union regulations have put particular emphasis on promoting sustainable alternatives to traditional chemical fertilizers. Regulation (EU) 2019/1009[39] features microbial biostimulants as a distinct category of fertilizing product, lists the microbial taxa that such products can contain and lays down rules on safety, quality and labelling.

Caradonia *et al.* (2018) describe legislative frameworks put in place for plant biostimulants in individual European countries and outside Europe (Brazil, Canada, India, South Africa and the United States of America). There is no global instrument regulating the use of biostimulants.

As with the use of BCAs, microorganisms utilized as biostimulants can trigger process and laws on ABS in provider countries. The relevant issues are covered Section 4.1.1 and Section 4.5. When organisms are accessed for use as biostimulants, prior informed consent and mutually agreed terms need to be negotiated with the provider country, and terms agreed for appropriate benefit-sharing where

[39] Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003.

applicable. The trigger for benefit-sharing is governed by national law and process and how they view the proposed uses of the genetic resources covered, which can differ from country to country.

Use of an organism as a biostimulant relies on both biological and chemical interactions with the plant, for example stimulation of the plant's immune system or facilitation or enhancement of other aspects of its metabolism. In many cases it is the organism itself that is applied as the biostimulant, but it can also be a chemical derived from the organism. The intervention could be, for example, the application of an antimicrobial or growth-stimulant hormone that is totally independent of the organism itself. The Nagoya Protocol (Article 2) defines "derivative" as a "naturally occurring biochemical compound resulting from the genetic expression or metabolism of biological or genetic resources, even if it does not contain functional units of heredity." Acquiring an organism to produce a derivative requires ABS negotiations with the provider country and agreement on the sharing of benefits derived from this use.

## 5.4 Challenges, needs and opportunities

Recent years have seen rapid growth in the number of published studies on microbial biostimulants and the development of relevant legal framework and legislation. These trends may improve the image of the industry and the efficacy of products (Yahkin *et al.*, 2017). Biostimulants will be used by growers if the expected benefits are clear and supported by fair marketing practices, including adequate labelling, and by a sound regulatory framework (du Jardin, 2020).

Challenges for the further development and adoption of biostimulants include the lack of publicly available data quantifying their benefits in commercial cropping systems at a large scale, despite the published evidence of the many effects they have on plants (du Jardin, 2020). With regard to market introduction, challenges to overcome include the following: high variation in product quality, which leads to difficulty in standardization and unreliable performance; incomplete knowledge of the physiological and molecular modes of action of biostimulant products; and lack of farmer awareness and knowledge of the specific benefits of biostimulant solutions and of the farming strategies that would synergize biostimulant effects and maximize impact at optimal costs (Bonini *et al.*, 2020).

# Chapter 6. Opportunities for action

The chapters above identify a range of gaps and needs in various aspects of the management of microbial and invertebrate BCAs and microbial biostimulants. This chapter summarizes key actions needed to address these gaps and needs and looks more specifically at the potential role of the Commission in this field. Section 6.1 presents general recommendations that might be addressed the Commission, its Members or any other stakeholders. Section 6.2 present a brief overview of the organizations working in this field and of existing guidelines and other instruments available to support management activities. Section 6.3 presents key areas where action is needed and that the Commission may wish to consider addressing in its future work.

## 6.1 General recommendations

Six general recommendations for the management of microbial and invertebrate BCAs were presented in Commission Background Study Paper No. 57 *The sustainable management of biodiversity for biological control in food and agriculture: status and needs* (Waage, 2007). While the policy context has in some respects changed, these recommendations generally remain relevant. Box 3 presents a revised and expanded version of the list of recommendations.

## 6.2 Resources

A range of regional and international intergovernmental organizations, research institutes and industry bodies concerned with agricultural development and/or the management of biodiversity form part of the institutional framework for the management of microbial and invertebrate BCAs and microbial biostimulants. Most have broad mandates within which the management of microbial and invertebrate BCAs and microbial biostimulants is only one element. A few organizations focus specifically on BCAs, for example the International Organization for Biological Control (IOBC),[40] its Global Commission on Biological Control and Access and Benefit Sharing[41] and its regional sections. Producers are represented by the International Biocontrol Manufacturers Association[42] and the Association of Natural Biocontrol Producers in North America.[43] A list of selected key organizations is presented in Annex I.

Stakeholders in the management of microbial and invertebrate BCAs and microbial biostimulants can draw on a range of tools and guidance related to work in this field. These include a variety of publications offering guidance on technical aspects of management and on the development of policy and legal frameworks, including on ABS. There are also several relevant publicly available databases and information systems. Selected tools and guidance materials are listed in Annex II.

## 6.3 Opportunities for the Commission

While Section 6.3 presents general recommendations on the sustainable management of microbial and invertebrate BCAs and microbial biostimulants, this section specifically considers potential opportunities for action by the Commission, particularly in the context of its efforts to support the implementation of the Framework for Action on Biodiversity for Food and Agriculture (FAO, 2022b).[44]

The needs and possible actions included in the Framework for Action are relatively general and do not refer specifically to the management of microbial and invertebrate BCAs or microbial biostimulants. However, both are important components of "associated biodiversity", a key focus of the Framework for Action. Thus, in principle, if the Framework for Action is implemented effectively, the management of BCAs and biostimulants should benefit. The subsections below look at some specific activities that will be needed and the potential role of the Commission in supporting them.

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[40] https://www.iobc-wprs.org/
[41] http://www.iobc-global.org/global_comm_bc_access_benefit_sharing.html

[42] https://ibma-global.org
[43] http://anbp.org/index.php
[44] The Framework for Action on Biodiversity for Food and Agriculture was endorsed by the Commission in 2019 as a global policy response to the report on *The State of the World's Biodiversity for Food and Agriculture* (FAO, 2019b). It sets out more than 50 actions grouped into three strategic priority areas: characterization, assessment and monitoring; management (sustainable use and conservation); and institutional frameworks.

**Box 3. Recommendations for the sustainable use and conservation of microbial and invertebrate biological control agents and biostimulants**

*Recommendation 1.* The conservation of natural enemies for biological control in crops and natural habitats should be an explicit objective in international standards on good agricultural practices and stewardship of natural areas, and in national and international policy for integrated pest management.

*Recommendation 2.* National and international measures should be taken to strengthen research, including public-sector research, on the taxonomy and use of biological control agents and to improve collections and other services (e.g. training of PhD-level scientists) and infrastructure (e.g. laboratories and quarantine facilities) that support biological control.

*Recommendation 3.* National and international measures should be taken to educate farmers and conservationists on the benefits of natural enemies and their management and to increase their participation in research and implementation in order to promote successful uptake of biological control.

*Recommendation 4.* National and international measures should be taken to promote community science initiatives that would engage the general public in the study and conservation of natural enemies.

*Recommendation 5.* National and international measures should be taken to improve knowledge of the negative effects of pesticides on natural enemies, and this knowledge should be made openly accessible for farmers.

*Recommendation 6.* The conservation of habitats of natural enemy species for biological control of future non-native pest problems in other countries should be an explicit element of national and international measures to conserve biodiversity in agroecosystems and natural ecosystems. Conservation and sustainable use of natural enemies can be further formalized and applied through conservation biological control practices.

*Recommendation 7.* Government authorities should adopt simplified measures for access to and exchange of biological control agents or consider exemption of these activities from the scope of access and benefit-sharing regimes.

*Recommendation 8.* Governments should develop appropriate national regulatory systems for biological control organisms that encourage and support the development of new agents for classical biological control and methods to enhance augmentative biological control. They should harmonize regulatory requirements and promote knowledge sharing at the international level to facilitate the development of effective biological control programmes.

*Recommendation 9.* In considering future measures for conservation and use of genetic resources for food and agriculture, governments should consider a broad approach to the conservation and sustainable use of biodiversity, including access to knowledge and capacity building: components of such an approach will help improve the management of biological control agents.

*Recommendation 10.* Governments should encourage initiatives that educate the public on the benefits of biological control, including its role in protecting the food supply (Sustainable Development Goal [SDG 2]), improving health (SDG 3), and reducing the negative impacts of agriculture on the environment (SDG 12) and the climate (SDG 13).

*Source*: Updated from Waage, J. 2007. *The sustainable management of biodiversity for biological control in food and agriculture: status and needs*. Background Study Paper No. 57. Commission on Genetic Resources for Food and Agriculture. Rome, FAO.

### Addressing threats to microbial and invertebrate BCAs and improving their conservation

As discussed in Chapter 2, like many other components of biodiversity for food and agriculture, microbial and invertebrate BCAs and microbial biostimulants are threatened by a variety of factors, including habitat destruction, climate change, invasive species and the use of pesticides. Efforts to address these threats and promote conservation measures for microbial and invertebrate BCAs and microbial biostimulants are urgently needed. Conservation is traditionally a key focus of the Commission's activities on any component of biodiversity for food and agriculture it addresses.

Other things being equal, microbial and invertebrate BCAs and microbial biostimulants can be expected to benefit from generic actions that lead to improvements in the conservation of microorganism and invertebrate biodiversity in and around production systems. However, some specific priorities can be identified.

With regard to conservation policy – including the use of incentive measures to promote biodiversity-friendly agricultural practices – there is a need to ensure that microbial and invertebrate BCAs and microbial biostimulants are given adequate attention and that measures specifically targeting them are developed and implemented.

With regard to the *ex situ* conservation of microorganisms, there is a need to promote and support coordination in the activities of culture-collection organizations. Any action in this regard will need to be carried out in collaboration with organizations active in this field at the global level (e.g. WFCC), regional level (e.g. MIRRI, ABRCN) and national[45] level. Moving from the storage of individual axenic cultures of microorganisms to the storage of whole communities (microbiomes) will help ensure more comprehensive *ex situ* conservation. There is a need to work with initiatives in this field to ensure that microorganisms that act as BCAs and biostimulants are fully considered and covered.

Promoting the *ex situ* conservation of invertebrate BCAs, particularly those species that have application in classical biological control and for which *in situ* conservation is limited or not possible, would be desirable. However, *ex situ* conservation of invertebrates remains technically challenging. There is a need to develop technologies and best practices that would ensure that the genetic integrity of invertebrate BCAs kept in living cultures can be maintained. Cooperation among countries to coordinate these activities for BCAs would also be needed.

### Promoting the sustainable use of microbial and invertebrate BCAs and microbial biostimulants

The potential of microbial and invertebrate BCAs and microbial biostimulants in the various sectors of food and agriculture remains underdeveloped. There is a need to continue the search for microbial and invertebrate BCAs and microbial biostimulants that have not yet been utilized and to develop applications for them, while also ensuring that the uptake of existing management strategies involving the use of BCAs and biostimulants is facilitated and promoted. This will require an enabling framework in terms of, *inter alia*, the state of knowledge, capacity, cooperation, policy and legislation (see subsections below). Across all these fields there is a need to support, engage with and involve producers who are users or potential users of microbial and invertebrate BCAs and microbial biostimulants.

Use could be promoted by ensuring that the implementation of damage thresholds is enforced and by adapting current thresholds so as to include BCA levels. Another area potentially needing attention is quality control of BCAs for augmentative releases. Options include, for example, the development of a protocol for quality control or best practices for companies providing BCAs.

Despite progress at the research level, genetic improvement of BCAs has had little practical impact to date. Constraints related, *inter alia*, to knowledge gaps and regulatory issues need to be addressed.

### Addressing constraints to the exchange of microbial and invertebrate BCAs and microbial biostimulants

As discussed in Chapter 4, exchange of microbial and invertebrate BCAs, including at international level, is vital to the development and implementation of biocontrol practices. Over recent years, exchanges have been affected by the existence and (inconsistent) implementation of the Nagoya Protocol. To date, Commission activities in this field have included coverage of microorganism and invertebrate genetic resources in the Elements to Facilitate Domestic Implementation of Access and Benefit-Sharing for Different Subsectors of Genetic Resources for Food and Agriculture and their explanatory notes (FAO, 2019c). Any further activities will need to ensure that the concerns of the biological control sector are taken into account. The

[45] See WFCC list http://www.wfcc.info/collections/networks/

development of a multilateral framework specifically aimed at facilitating access to and use of BCAs and the sharing of benefits arising from their utilization could potentially be considered.

### Addressing knowledge gaps on microbial and invertebrate BCAs and microbial biostimulants and their management

Improvements to the management of microbial and invertebrate BCAs and microbial biostimulants require knowledge of the characteristics of these organisms, their roles in the supply of ecosystem services, their risk status and distribution, and the threats affecting them. They also require knowledge of the state of the art in use and conservation of these organisms and of the status and trends of management actions affecting them. Assessment and monitoring of genetic resources and biodiversity – both overseeing the collection, management and diffusion of data at global level and supporting action at country level – have traditionally been key Commission activities.

Research on the management of microbial and invertebrate BCAs and microbial biostimulants can potentially be facilitated via capacity development, promoting access to data and information, developing or strengthening policy and legal frameworks, and promoting collaboration among researchers and between them and other stakeholders (see subsections below for further discussion of these issues).

### Improving capacity development in the management of BCAs and biostimulants

As discussed in the chapters above, there is a critical lack of human and material resources for the identification and characterization of BCAs and biostimulants, especially those that provide natural or conservation biological control. Support for surveying and inventory of microbial and invertebrate BCAs and microbial biostimulants needs to be stepped up, particularly in tropical and subtropical areas. An important aspect of this will be the use of DSI (currently involving DNA barcodes based on specific short sequences but in future likely to involve more sophisticated techniques such those based on multiple sequences and genomes). The skills and tools needed to extract, analyse and interpret such information are currently limited in most parts of the world, and these gaps need to be addressed. Unrestricted multilateral sharing of DSI that supports the identification of BCAs and other species of agricultural importance (e.g. though open-access databases such as GenBank and BOLD) is essential if work in this field is to fulfil its potential. Genetic-based identification needs to be supported with traditional taxonomic, morphology-based descriptions and binomial naming of species. Molecular and morphological approaches are complementary and need to be used in tandem. Researchers need to be trained to recognize, at least to the family level, the BCAs that they are collecting in the field. This can only be done via visual observation, as it is impossible to do molecular-based identifications in near-real time as material is being collected.

The Commission has, over the years, developed or endorsed guidelines on various technical aspects of genetic resources management, mostly for animal (livestock) and plant genetic resources and mostly covering aspects of conservation, characterization and breeding. It could potentially consider whether there is any need for such instruments or publications in the case of microbial and invertebrate BCAs and microbial biostimulants and whether it is in a position to address this need, including, as relevant, what kinds of collaborative partnerships with other organizations might be needed in this regard.

### Developing, improving or harmonizing policy and legal frameworks for the management of microbial and invertebrate BCAs and microbial biostimulants

The management of microbial and invertebrate BCAs and microbial biostimulants is influenced by policies and legislation in a range of fields, including those related to the registration of pest control products, plant health, invasive alien species, regulation of the use of pesticides, biodiversity conservation, promotion of IPM, science, technology and innovation, and ABS.

Microbial and invertebrate BCAs and microbial biostimulants are often neglected in national policy and legal frameworks, and relevant instruments are sometimes poorly implemented. The Commission could potentially consider what role it could play in terms of raising awareness or providing guidance in this field. Existing tools and guidelines will need to be taken into account and options for collaboration with other organizations working in this field explored.

### Improving diffusion of knowledge on microbial and invertebrate BCAs and microbial biostimulants

As noted above, promoting the diffusion of knowledge related to genetic resources and biodiversity and their management is a major aspect of the Commission's work, whether via the outputs of global assessments, reporting on the implementation of global plans of action, the publication of guidelines or the operation of information systems such as the Domestic Animal Diversity Information System(DAD-IS)[46] and the World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (WIEWS).[47]

The Commission could potentially consider what it could do in this regard for microbial and invertebrate BCAs and microbial biostimulants. Action in this field might, for example, involve support for an online knowledge portal featuring items such as relevant national policy frameworks and metrics of biological control impacts, or more dynamic virtual communities of practice and associated multistakeholder innovation platforms (see below for further discussion of opportunities to promote networking). Developing an inventory of microbial and invertebrate BCAs and microbial biostimulants used around the globe, including information on source and user countries, on production systems and environments where organisms are used and on target species, could be considered. Existing tools for knowledge diffusion need to be taken into account and promoted and options explored for collaboration with other organizations working in the field.

More generally, there is a need to encourage and support the diffusion of knowledge on microbial and invertebrate BCAs and microbial biostimulants among relevant stakeholders. Options for this knowledge diffusion could potentially include giving greater attention to microbial and invertebrate BCAs and microbial biostimulants in the curricula of universities, agricultural colleges and schools, reinstating or extending independent farming extension services that can support farmers in the choice of landscape elements that are effective in terms of conservation biocontrol and in the implementation of augmentative biocontrol, and establishing demonstration farms that feature microbial and invertebrate BCAs and microbial biostimulants. Perhaps most importantly, increasing opportunities and funding support for training of new scientists that specialize in biological control is needed if the above suggestions are to be implemented globally.

### Improving cooperation and networking among those working on/with BCAs and biostimulants

Action in all the areas discussed above would benefit from improved cooperation and networking among stakeholders, and consistent funding over the medium to long term for nascent collaborative programmes is needed. One priority needs to be stimulating cooperation between producers to generate synergies in the use of BCAs at the landscape level. The Commission could potentially consider what it can do to promote objectives of these kinds. This might include, for example, supporting the establishment of networking platforms that facilitate the identification of expertise for country-level, regional or wider collaborative initiatives, including, in the case of classical biological control programmes, the identification of collaborators in the region of origin of invasive pests. Another option could be stimulating the establishment and operation of research incubators, innovation hubs and working groups covering different aspects of biological control. These could operate at regional or interregional level and could serve as platforms for delivering relevant expertise to developing countries.

### Mainstreaming microbial and invertebrate BCAs and microbial biostimulants into biodiversity, environmental and agricultural policy and practice

The use and conservation of microbial and invertebrate BCAs and microbial biostimulants are relevant to many policy objectives and potentially affected by a range of different policies. Relevant policy areas include climate change, sustainable food systems (including agricultural pollution mitigation), general biodiversity conservation (including restoration) and sustainable use, and One Health. The Commission could potentially consider what awareness-raising or facilitating role it might play in terms of ensuring that microbial and invertebrate BCAs and microbial biostimulants are adequately taken into account in policy dialogues and in UN-level working groups, joint commissions or funds.

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[46] http://www.fao.org/dad-is/data/en
[47] https://www.fao.org/wiews/en

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# Annex I. Selected organizations contributing to the international institutional framework for the management of microbial and invertebrate biological control agents and microbial biostimulants

### Global and regional science/research organizations

- Agroecology Europe (https://www.agroecology-europe.org)
- Centre for Agriculture and Bioscience International (CABI) (https://www.cabi.org)
- Euphresco (https://www.euphresco.net/)
- CGIAR centres (https://www.cgiar.org) such as:
  - International Maize and Wheat Improvement Center (CIMMYT) (https://www.cimmyt.org)
  - International Food Policy Research Institute (IFPRI) (https://www.ifpri.org))
  - International Institute of Tropical Agriculture (IITA) (https://www.iita.org)
  - World Agroforestry (ICRAF) (https://www.worldagroforestry.org)
- International Centre of Insect Physiology and Ecology (ICIPE) (http://www.icipe.org)
- Inter-American Institute for Cooperation on Agriculture (IICA) (https://www.iica.int/en)
- International Organization of Biological Control (IOBC) (https://www.iobc-wprs.org/), its Global Commission on Biological Control and Access and Benefit Sharing (http://www.iobc-global.org/global_comm_bc_access_benefit_sharing.html) and its regional sections.
- International Institute for Sustainable Development (http://sdg.iisd.org)
- International Union for Conservation of Nature (IUCN) (https://www.iucn.org)
- Organization of Tropical Studies (OTS) (https://tropicalstudies.org)
- Southeast Asian Ministers of Education Organization (SEAMEO) (https://www.seameo.org/w5) institutions such as
  - BIOTROP (https://www.biotrop.org/)
  - SEARCA (https://www.searca.org/)
- Sociedad Cientifica Latinoamericana de Agroecologia (Latin American Scientific Society of Agroecology) (SOCLA) (https://soclaglobal.com/)

There is also considerable research capacity within industry in terms of developing new BCAs and new use strategies (see section on industry bodies below)

### Organizations involved in coordinating *ex situ* conservation of microorganisms

- Asian Consortium for the Conservation and Sustainable Use of Microbial Resources (ACM), which has established a task force to establish the Asian BRC Network (ABRCN) (https://www.acm-mrc.asia)
- Microbial Resource Research Infrastructure (MIRRI) (https://www.mirri.org)
- World Federation for Culture Collections (WFCC) (www.wfcc.info), a multidisciplinary commission of the International Union of Biological Sciences (IUBS) and a Federation within the International Union of Microbiological Societies (IUMS).

### Global and regional governmental organizations

- African, Caribbean and Pacific Group of States (http://www.acp.int)
- Association of Southeast Asian Nations (ASEAN) (https://asean.org)
- Comité de Sanidad Vegetal (COSAVE) (http://www.cosave.org/pagina/bienvenidos-al-comite-de-sanidad-vegetal-cosave)
- Convention on Biological Diversity (CBD) ) (https://www.cbd.int)
- Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (https://ipbes.net)
- International Plant Protection Convention (IPPC) (https://www.ippc.int/en) and its regional entities
- Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture (https://www.iaea.org/about/organizational-structure/department-of-nuclear-sciences-and-applications/joint-fao/iaea-centre-of-nuclear-techniques-in-food-and-agriculture)
- Organisation for Economic Co-operation and Development (OECD) task force on Biological Resource Centres (BRCs) (https://www.oecd.org/sti/emerging-tech/biologicalresourcecentres.htm).
- United Nations Environment Programme (https://www.unep.org)
- United Nations Development Programme Global Environment Facility Global Access and Benefit Sharing Project ((UNDP GEF GABSP) (https://abs-sustainabledevelopment.net)

### Global and regional industry bodies

International Biocontrol Manufacturers Association (https://ibma-global.org)

Selected examples of national organizations

- Argentina: Comisión Nacional Asesora para la Conservación y Utilización Sostenible de la Diversidad Biológica (Conadibio), Ministerio de Ambiente y Desarrollo Sostenible (https://www.argentina.gob.ar/ambiente/biodiversidad/conadibio); Comisión Nacional Asesora sobre los Recursos Genéticos para la Alimentación y la Agricultura (CONARGEN) y Comité Asesor en Bioinsumos de Uso Agropecuario (CABUA), Ministerio de Agricultura, Ganadería y Pesca; Red de Recursos Genéticos-RedGen Instituto Nacional de Tecnología Agropecuaria (INTA) (https://inta.gob.ar/proyectos/red-de-recursos-geneticos)
- Australia: Commonwealth Scientific and Industrial Research Organisation (CSIRO) (https://www.csiro.au/en) (specifically on weed biological control)
- Belgium: Belgian Co-ordinated Collections of Microorganisms-BCCM (https://bccm.belspo.be)
- Brazil: Brazilian Agricultural Research Corporation (Embrapa) (https://www.embrapa.br/tema-controle-biologico)
- Canada: Agriculture and Agri-Food Canada (AAFC) (https://www.agriculture.canada.ca/en)
- China: Chinese Academy of Agricultural Sciences Joint International Research Laboratory of Ecological Pest Control (http://www.caas.cn/en/index.html)
- France: CIRAD (https://www.cirad.fr/en) in alliance with INRAE (https://www.inrae.fr/en) and IRD (https://en.ird.fr) (France)
- Germany: GIZ (https://www.giz.de/en/html/index.html)
- Mexico: Federal agencies, such as COFEPRIS, CONABIO, SEMARNAT, National Food Sanitary, Safety and Quality Service (SENASICA), and research institutes (CONACyT Centers, CINVESTAV, Colegio de Postgraduados, INECOL), among others.
- New Zealand: Bioprotection Center New Zealand
- United States of America: Smithsonian Institution (https://www.si.edu) (specifically on biodiversity discovery); United States Department of Agriculture; ANBP (http://anbp.org/index.php)
- Sweden: Swedish International Agricultural Network Initiative (SIANI) (https://www.siani.se)

# Annex II. Selected tools and guidance for the management of microbial and invertebrate biological control agents and microbial biostimulants

## Guidelines, standards and other publications offering guidance and advice

**Barratt, B.I.P., Mason, P.G., Cock, M.J.W., Klapwijk, J., van Lenteren, J.C., Brodeur, J., Hoelmer, K.A. & Heimpel, G.E.** 2017. Access and benefit sharing: best practices for the use and exchange of invertebrate biological control agents. In: P.G. Mason, D.R. Gillespie & C. Vincent, eds. *Proceedings of the 5th International Symposium on Biological Control of Arthropods, Langkawi, Malaysia September 11–15, 2017*, pp. 71–74. Wallingford, UK, CAB International.

**Bateman, R., Ginting, S., Moltmann, J. & Jäkel, T.** 2014. *ASEAN Guidelines on the Regulation, Use, and Trade of Biological Control Agents (BCA). Implementing Biological Control Agents in the ASEAN Region: Guidelines for Policy Makers and Practitioners.* ASEAN. www.asean-agrifood.org/?wpfb_dl=57

**Belgian Co-ordinated Collections of Micro-organisms.** 2011. *Micro-Organisms Sustainable use and Access Regulation International Code of Conduct.* https://bccm.belspo.be/projects/mosaicc

**Candolfi, M.P., Blumel, S., Foster, R., Bakker, F.M., Grimm, C., Hassan, S.A., Heimbach, U., Mead-Briggs, M. A., Reber, B., Schmuck, R., Vogt, H.,** eds. 2000. *Guidelines to evaluate side-effects of plant protection products to non-target arthropods.* Gent, Belgium, IOBC/WPRS.

**CBD.** 2016. Summary of technical considerations for the use of biological control agents to manage invasive alien species. Annex. *Invasive alien species: addressing risks associated with trade, experiences in the use of biological control agents, and decision support tool.* Decision adopted by the Conference of the Parties to the Convention on Biological Diversity Thirteenth meeting, Cancun, Mexico, 4–17 December 2016. CBD/COP/DEC/XIII/13. Montreal, Canada, Secretariat of the Convention on Biological Diversity. www.cbd.int/doc/decisions/cop-13/cop-13-dec-13-en.pdf

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**Consortium of European Taxonomic Facilities (CETAF).** *Code of Conduct and Best Practices on Access and Benefit-Sharing* https://cetaf.org/sites/default/files/final_cetaf_abs_coc.pdf

**European and Mediterranean Plant Protection Organization (website)** *EPPO Standards – PM 6 Safe use of biological control.* www.eppo.int/RESOURCES/eppo_standards/pm6_biocontrol

**European and Mediterranean Plant Protection Organization**. 2018. PM 6/04 (1) Decision-support scheme for import and release of biological control agents of plant pests. *Bulletin OEPP/EPPO Bulletin*, 48: 352–367 ISSN 0250-8052. DOI: 10.1111/epp.12495

**Global Genome Biodiversity Network.** 2015. *Global Genome Biodiversity Network (GGBN) guidance: best practice or access and benefit-sharing ABS.* Washington, DC, GGBN Secretariat. https://library.ggbn.org/share/s/546z-VMjjQTKnv44lqXvkGQ

**Hassan, S., ed,** 1992. *Guidelines for testing the effects of pesticides on beneficial organisms: description of test methods.* International Organization for Biological and Integrated Control of Noxious Animals and Plants/Working Group Pesticides and Beneficial Organisms. IOBC/WPRS Bull. XV/3.

**Hoeschle-Zeledon, I., Neuenschwander, P. & Kumar, L.** 2013. *Regulatory challenges for biological control.* System-wide Program on Integrated Pest Management. Ibadan, Nigeria, IITA. https://hdl.handle.net/10568/80836

**International Plant Protection Convention (website)** International Standards for Phytosanitary Measures. www.ippc.int/en/core-activities/standards-setting/ispms

**Mason, P.G., Cock, M.J.W., Barratt, B.I.P., Klapwijk, J.N., van Lenteren, J.C., Brodeur, J., Hoelmer, K.A. & Heimpel. G.E.** 2017. Best practices for the use and exchange of invertebrate biological control genetic resources relevant for food and agriculture. *BioControl*, 63: 149–154.

**Organisation for Economic Co-operation and Development.** 2012. *Guidance to the environmental safety evaluation of microbial biocontrol agents.* Series on Pesticides No. 67. Paris. www.oecd.org/env/oecd-guidance-to-the-environmental-safety-evaluation-of-microbial-biocontrol-agents-9789264221659-en.htm

**Organisation for Economic Co-operation and Development.** 2003. *Guidance for registration requirements for microbial pesticides.* Series on Pesticides No. 18. Paris. www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=env/jm/mono(2003)5&doclanguage=en

**Organisation for Economic Co-operation and Development.** 2003. *Guidance for information requirements for regulation of invertebrates as biological control agents (IBCAs).* Series on Pesticides No. 21. Paris. www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=env/jm/mono(2004)1&doclanguage=en

**Paula, D.P., Andow, D.A., Barratt, B.I.P., Pfannenstiel, R.S., Gerard, P.J., Todd, J.H., Zaviezo, *et al.*** 2020. Integrating adverse effect analysis into environmental risk assessment for exotic generalist arthropod biological control agents: a three-tiered framework. *BioControl*, 66: 113–139.

**Sheppard, A.W., Paynter, Q., Mason, P., Murphy, S., Stoett, P., Cowan, P., Brodeur, J., Warner, K., Villegas, C., Shaw, R., Hinz, H., Hill, M. & Genovesi, P.** 2019. *IUCN SSC Invasive Species Specialist Group. The application of biological control for the management of established invasive alien species causing environmental impacts.* CBD Technical Series No. 91. Montreal, Canada, Secretariat of the Convention on Biological Diversity.

**Van Driesche, R.G., Simberloff, D., Blossey, B, Causton, C., Hoddle, M.S., Wagner, D.L., Marks, C.O., Heinz, K.M. & Warner, K.D., eds**. 2016. *Integrating biological control into conservation practice.* Chichester, UK, John Wiley & Sons, Ltd.

**Van Lenteren, J.C., Bueno, V.H.P., Luna, M.G. & Colmenarez, Y.C., eds.** 2020. *Biological control in Latin America and the Caribbean: Its rich history and bright future.* CABI Invasives Series; Vol. 12. Wallingford, UK, CABI.

## Databases and information systems

BIOCAT (a database of introductions of insect BCAs for classical biological control of insects) (non-public)

WBC database (a database of BCAs used in biological control of weeds and their targets) (https://www.ibiocontrol.org/catalog/)

CABI Bioprotection Portal (provides information about registered biocontrol and biopesticide products around the world) (https://bioprotectionportal.com),

IOBC database of pesticides selectivity to beneficial arthropods and insect pathogens (https://www.iobc-wprs.org/restricted_member/toolbox.cfm) (available for IOBC members).

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