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The status of biological control and recommendations for improving uptake for the future

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Abstract Classical and augmentative biological control of insect pests and weeds has enjoyed a long history of successes. However, biocontrol practices have not been as universally accepted or optimally utilised as they could be. An International Organisation for Biological Control (IOBC) initiative brought together practitioners and researchers from widely diverse fields to identify the main limitations to biocontrol uptake and to recommend means of mitigation. Limitations to uptake included: risk averse and unwieldy regulatory processes; increasingly bureaucratic barriers to access to biocontrol agents; insufficient engagement and communication with the public, stakeholders, growers and politicians of the considerable economic benefits of biocontrol; and fragmentation of biocontrol sub-disciplines. In this contribution we summarise a range of recommendations for the future that emphasise the need for improved communication of economic, environmental and social successes and benefits of biological control for insect pests, weeds and plant diseases, targeting political, regulatory, grower/land manager and other stakeholder interests. Political initiatives in some countries which augur well for biocontrol in the future are discussed.

Keywords Biological control · IPM · Risk assessment · Access and benefit-sharing · Communication · Cost-effectiveness · Research approach

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Introduction

Biological control is defined as a method for insect, weed and disease management using natural enemies. Biological control has been used for centuries, but the first big wave of activity in the modern era followed the spectacular success of the introduction in the late 1880s of the parasitic fly, *Cryptochaetum iceryae* (Williston) (Diptera: Cryptochaetidae), and the vedalia beetle, *Rodolia cardinalis* (Mulsant) (Coleoptera: Coccinellidae) to control cottony-cushion scale (*Icerya purchasi* Maskell) (Hemiptera: Monophlebidae) in California citrus orchards (Caltagirone 1981). However, in the mid-1940s' the growth and success of the synthetic pesticide industry caused biocontrol use to almost disappear until the publication of Rachael Carson's 'Silent Spring' (Carson 1962), which decried the use of agricultural pesticides emphasizing deleterious environmental impacts on wildlife. Public protest as a result of this controversial book resulted in a demand for alternatives to pesticides, and opened an opportunity for greater application of biological control (Barratt et al. 2010; Gay 2012). Hardly had this controversy died down, when biological control then became the focus of scrutiny with suggestions that non-intended effects of biological control were a threat to the environment and were potentially causing non-target species to become extinct (Howarth 1983, 1991; Clarke et al. 1984). This perception polarised the research community for some years. Biocontrol practitioners who were researching alternatives to chemical pesticides were aggrieved at the accusations from environmentalists, particularly in the USA, that they were irreversibly introducing new species that would spread and reproduce, with no regard to species other than pests that might be attacked by these natural enemies. The debate in the USA was acrimonious and at times heated (Lockwood et al. 2001), while elsewhere, this debate was followed with considerable interest.

Ultimately, funding agencies made resources available to address the questions of non-target effects, and regulators started to require risk assessments for biocontrol proposals (Sheppard et al. 2003). It became clear that an opportunity had become available for some elegant ecological research to be done (Waage 2001), which could expand the scope of biocontrol from its primary focus on exploration, testing and release of natural enemies, to the realms of theoretical and applied ecology in which risk assessment could become an integral part. These developments seemed to rationalize and provide some common ground for opposing views on the wisdom, or otherwise, of biocontrol as a pest management practice (McEvoy and Coombs 2000; Hopper 1998).

In more recent years, it has become evident that a number of factors in combination, have served to undermine biocontrol practice. In California, USA, Warner et al. (2011) reviewed public interest in biological control in institutions and attributed the decline of biocontrol activity to revised priorities for universities, increasing specialisation of biocontrol science combined with difficulties that growers and interest groups have in influencing science. DiTomaso et al. (2017) referred to regulatory and political 'hurdles' which hinder biological control practice in the USA. Recently the President of the International Organisation for Biological Control (IOBC)-Nearctic Regional Section (NRS), reported to the IOBC Global General Assembly (September 2016) that there has been strong erosion of biocontrol research positions in US institutes, and that biocontrol is losing ground as an academic discipline (D. Weber, pers. comm. 2016; Messing and Brodeur 2017). Similarly, the President of IOBC Asia Pacific Regional Section has also noted erosion of weed biocontrol research positions in Australia (Palmer et al. 2014). However, this trend has been less apparent in other parts of the world, for example in Europe (van Lenteren et al. 2017) where biocontrol is still a widely adopted alternative to pesticides.

For weed biological control, an overall account of the current and potential future state of science and research is given in a recent and definitive text (Hatcher and Froud-Williams 2017). The problems detracting from the image of weed biocontrol were summarised by Moran and Hoffmann (2015) who analysed attendances at the international symposia on biological control of weeds from 1969 to 2014. The authors found that conference attendance figures were decreasing and that the discipline itself was in decline (except in New Zealand and South Africa), and attributed this decline to risk aversion, and exaggerated claims of adverse non-target impacts. In Australia, historically a world leader in weed biological control, research capacity had recently become reduced to about 20% of what it was in the 1980s and early 1990s (Sheppard et al. 2015; Palmer et al. 2014), although very recently there has been a little more investment in this area (A. Sheppard pers. comm.).

The International Organisation for Biological Control (IOBC; http://www.iobc-global.org/index.html) is a global organisation dedicated to the promotion of environmentally safe methods of insect, weed and disease control. As an independent professional organisation, IOBC is an effective advocate for biological control, and can potentially influence policy makers and governments. Established in 1955, IOBC operates internationally via geographical Regional Sections and topic-focussed working groups (global and regional). The organisation promotes national and international research, training of personnel, coordination of large-scale application and public awareness of the economic and social importance of biological control. IOBC arranges conferences, meetings and symposia, and takes other action to implement the general objectives of the organisation. The Executive Committee of IOBC Global became increasingly aware over the last few years that, although the need for environmentally safe pest management methods are theoretically in demand, the research capability and freedom to operate are in some regions being eroded, and for these and other reasons, adoption of biological control is often frustratingly slow.

While biological control is still seen by many as a preferable and sustainable alternative for chemical pest control, we consider that it should play a much more important role in managing insects, weeds and diseases. The IOBC recognised that it was timely to analyse and address issues hindering adoption of biological control, and to suggest solutions and a way forward. In order to assist IOBC in developing ideas to stimulate research and application of biological control for the future, a meeting designed to bring together a wide diversity of experience, geographical backgrounds, and aspects of biocontrol practice was held in October 2015. This proved to be a productive forum for debate and discussion. The details of some of these issues have been presented in the foregoing chapters in this Special Issue, and here we have analysed and summarised those discussions, and we report on recommendations for the future, and the envisaged role of the IOBC.

Biological control: current issues and solutions

Regulations concerning environmental risk

Biological control has been increasingly a focus for regulators over the last 20 years or so with many countries requiring risk assessments to be carried out to try to predict environmental risk. Some countries require analyses of risks and benefits, and decisions are made on the basis of this balance (ERMA New Zealand 1998; Sheppard et al. 2003; Klein et al. 2011), whereas others, such as Australia, do not consider benefits as part of the standard regulatory process because the target status of the pest has already been accepted (Sheppard et al. 2003). Post-release studies to validate decisions are rarely required by regulators, but where these studies are conducted, very valuable information can be made available and used in future decision support (Barratt 2011). Further research such as this to validate predictions made pre-release can only improve our ability to more accurately predict success and safety of biological control.

In a risk-averse society, regulations can become very constrictive, and risk assessment requirements tend to become very stringent. In such an environment, it seems that regulators find it easier to block decisions of biological control agent release, than to approve them. But, then the danger is that applications for good agents are declined (e.g. van Wilgen et al. 2013). In addition, it has been repeatedly articulated that trying to make progress with biological control under risk averse and highly bureaucratic circumstances can hold up implementation to such an extent that the practice of biological control becomes unrewarding and simply frustrating (Messing 2000; DiTomaso et al. 2017; Messing and Wright 2006). Researchers have become disenchanted with the system and fewer scientists are seeing a career path in classical biological control (Moran and Hoffmann 2015). In Australia several agents have been unnecessarily delayed through the approval processes possibly because of unreasonably high risk aversion and limited expertise remaining within the regulatory agencies (W. Palmer, pers. comm. 2017). Some countries such as New Zealand effectively avoid such regulatory delays by having a maximum statutory period (currently 100 working days from formal receipt of the application to a decision being made) within which the regulatory process must be completed.

Biological control practitioners, particularly in Europe, initially in an EU funded IOBC/biocontrol industry working group (van Lenteren et al. 2003, 2006), and later under the auspices of an IOBC-West Palearctic Regional Section (WPRS) Commission, made progress on developing and facilitating a harmonized, simplified environmental risk assessment methodology. This included a standardised system for import and study of exotic species for commercial release purposes (OEPP/EPPO 2014). However, achieving complete harmonization in Europe failed, and regulation is now up to individual countries using their own, highly variable regulatory system (Bigler et al. 2005, 2006; Bale 2011). This has resulted in an inefficient, expensive and time consuming process to register natural enemies for many small countries, as well as for small-scale producers of natural enemies. Lack of information and understanding of biological control practice and appreciation of successes is contributing to the development of a risk-averse culture in the public and the regulatory arena. Consequently, an undertaking by IOBC to provide fit-for-purpose resource material designed to address this situation might be advantageous. This is discussed in more detail below.

Regulations concerning access and benefit sharing

One of the objectives of the Convention on Biological Diversity (CBD) is “the fair and equitable sharing of the benefits arising out of utilisation of genetic resources” (Convention on Biological Diversity 1993). This is known as ‘Access and Benefit Sharing’ (ABS). It is recognised that countries have sovereign rights over their genetic resources and that agreements governing access to them, and benefits arising from their use should be established. The Nagoya Protocol, adopted in 2010 is the instrument for the implementation of ABS (Secretariat of the Convention on Biological Diversity 2011). ABS was recognised early on by IOBC as a risk for biological control practitioners who would have to comply with these requirements, potentially introducing considerable bureaucracy to the process of exploration and utilisation of biocontrol agents (Cock et al. 2010).

IOBC Global formed a Global Commission on Biological Control and ABS which was established initially to report to the Food and Agriculture Organization of the United Nations (FAO). CABI was subsequently requested to contribute to writing the report, which, when completed, contributed to the programme of the FAO Commission on Genetic Resources for Food and Agriculture (Cock and van Lenteren 2009; Cock et al. 2009). The IOBC Commission carried out a review of biocontrol practice globally, and pointed out the features of biocontrol that should exempt it from being considered part of a protocol that was essentially designed to protect countries from being exploited for profit by large commercial companies such as those within the pharmaceutical industry. The IOBC Commission made a number of recommendations which have been presented at policy meetings related to ABS. The IOBC Commission has subsequently met a request to produce a further document describing ‘best practice’ for ABS in relation to biological control (Mason et al. 2017).

The IOBC will continue to work with the CBD, CABI, FAO and other agencies whenever possible to provide information, resources etc. that can further promote the case for biological control deserving ‘special considerations’ under the Nagoya Protocol (CBD 2011, article 8) and to support systems that both comply with the Nagoya protocol but also facilitate the implementation of biological control.

In response to another CBD objective, an expert workshop on the risks and benefits of classical biological control for the management of invasive alien species, acknowledged classical biological control as “an effective management approach either by itself or as a component of integrated invasive alien species management for widespread invasive alien species” (Sheppard and Genovesi 2016).

Communication with stakeholders and the public

Stakeholders (including managers of productive and conservation lands) and the public are usually poorly informed about biological control, and indeed sometimes dismiss it as a feasible or desirable option for pest management. In conservation land, biological control has historically not been well integrated into management practice, although increasingly, successful projects have been undertaken (van Driesche and Rearden 2017). van Driesche (2017) outlined the history of biocontrol in natural areas and outlined some of the social and regulatory aspects associated with successful implementation.

The public often express negative views on biocontrol, usually supported by historic examples such as vertebrates that have been used for biocontrol, with negative impacts. The introduction of cane toads in Australia, mongoose in Hawaii (Else 2011), etc. are examples often luridly and repeatedly publicised, which perpetuate and erode public support for biocontrol, despite the very large number of successes with which they can be countered. These spectacular failures occurred during a time when there was little if any scientific oversight of the initial pest problem, or the consequences of the introduction. Similarly, cases where scientific data are manipulated to show unwanted effects of releases of exotic natural enemies can have a long-term negative effect on the use of biological control (see Messing, this issue).

As noted above, the IOBC intends to produce and widely disseminate a fit-for-purpose publication in an accessible format that can inform a range of non-specialist interest and policy groups, as well as the public with positive evidence about biological control benefits. As a first step, the IOBC will publish a concise, well-illustrated compendium of brief case-studies showing successful biological control achieved across a range of agents and targets, geographical regions and sectors. Such a publication would be aimed at regulators, stakeholders, policy groups, students and the public, and would serve as an educational tool and information resource to expel some of the negative misinformation about biological control, and to promote the positive benefits and successes.

Biocontrol practitioners could assist in reversing some of the misconceptions about biological control by communicating the benefits of their work, not only in the scientific literature, but also verbally and in popular publications. Furthermore, it might be prudent to 'sell' biocontrol not as just a way to reduce pests, but at a higher outcome-focussed level. For example, in natural ecosystems, the outcome for a successful biological control programme might be ecological restoration, or avoiding environmental harm from pesticides. For productive systems the outcome goal could be phrased in terms of socio-economic impacts, such a reduction in greenhouse gas emissions (Heimpel et al. 2013).

The complexity of integrated pest management (IPM)

IPM, and biological control as a component of it, can be relatively complex systems involving many stakeholders that may have specific expectations and requirements. Changing management practices is challenging and may entail economic risks for growers and, to a lesser extent, for managers of conservation land. Therefore, farmers and land-managers need to be able to understand what they are being advised to do and why, and they generally want to see a financial benefit, at least in the longer term, from adopting new or different practices. If they decide they do want to adopt new pest management methods they need to invest time for training, monitoring, and implementation in their specific environment (e.g. van Lenteren et al. 2017).

New technologies using no or less pesticides may add value to farm produce and the environment and thus open new opportunities to sell IPM products in saturated food markets (Lefebvre et al. 2015). Major motivations for growers to change from a pesticide-based management system to IPM are direct and indirect economic benefits (e.g. subsidies, free advisory service, improved market access for products), avoidance of pest resistance to pesticides, and regulation to protect the environment and humans from exposure to pesticides. Studies comparing how European consumers value IPM compared to conventionally grown products have shown that consumers are willing to pay higher prices for IPM products. However, the price premium observed is often quite low (Lefebvre et al. 2015). These authors concluded that marketing IPM products is difficult and the premium is not a major incentive to farmers in the absence of an official European label. Currently there are 56 different and certified schemes (labels) for foodstuff in the European Union that relate to Integrated Production and IPM, and this may be an obstacle to the better adoption of IPM, and uptake by consumers.

Governments and policy can promote and sustainably support biocontrol and IPM in three different ways outlined by the Organisation for Economic Cooperation and Development (OECD) (OECD 2012). Firstly there is an outcome-based policy where the government sets goals of risk reduction through the application of biological control and IPM while leaving implementation and achieving the goals in the hands of market forces; secondly a facilitative policy where the government uses policy measures as an incentive to make the uptake of biocontrol and IPM attractive to farmers by supporting a broad suite of tools for research, knowledge transfer, decision making support and stakeholder involvement; and thirdly a prescriptive policy with the government setting goals and laying out specific expectations for implementation through regulations, requirements and checklists. The OECD in its report (OECD 2012) recommends that governments should apply in general a facilitative policy to foster IPM uptake by creating incentives including short and long-term financial mechanisms and support to ensure continuity and sustainability of IPM, and prevent growers reverting to conventional, pesticide-based production. As an example, while the European Union has made IPM mandatory for all farmers as from 1st January 2014 onwards (European Union 2009), an increase in advisory services has been identified as an important indirect subsidy to support farmers with the necessary technical and economical knowledge for IPM adoption (Lefebvre et al. 2015).

To increase adoption of biological control within IPM systems, timely integration of growers and extension advisors in the decision-making process is vital to help overcome negative attitudes towards these methods. Growers/managers and advisors need to understand the benefits and risks of introducing IPM to an existing crop/natural ecosystem compared to their continuing practices. Not only do IPM practitioners need to provide support to farmers and managers in understanding the complexity of IPM systems, especially where biocontrol is a key component, but researchers also need to understand the environment within which these tools are to be used. A partnership developed at an early stage between researchers, extension specialists and growers is likely to result in the best outcome for all parties. In this context, private or public extension advisory services are considered to be key players (OECD 2012). Sustained use of IPM by growers so that they are able to experience the longer-term benefits needs to be encouraged, and to avoid farmers reverting to conventional production systems when problems occur.

Communication and information provided by scientists should be easily comprehensible and in a plain language adapted to the needs of stakeholders and taking account of regional differences. This is particularly true in developing countries where language, long-standing traditions, and the need for quick returns are issues that are hard to overcome. The introduction of a more participatory approach where researchers and consultants can assist groups of farmers to attend training sessions or 'farmer field schools' (FFSs) has been successfully used by FAO, CABI and other overseas aid agencies. Farmers can attend FFSs and grow crops in a communal environment where they learn how to observe pest problems, and discuss IPM methods interactively with their peers and trainers (e.g. see Wyckhuys, this issue).

Modern methods of communication are becoming more affordable and available in both developed and developing countries. Smart phones, tablets and computers are tools that can be successfully used to support and strengthen decision-making by growers. This movement towards ICT-based Extension (Information Communication Technology) is becoming a powerful tool which can reach a very large number of farmers with timely and simple to follow advice. There are many initiatives for ICT extension which provide pest-related information, seasonal alerts, field identification, distribution maps, fact sheets and publications, throughout the world for which access is possible on smart phones and other devices. One of the most comprehensive is the CABI-led Plantwise programme supporting the Plantwise Knowledge bank (CABI 2016). Working in national partnerships Plantwise has also established plant clinics around the world, particularly in developing countries, run by trained extension officers which provide support through pest diagnoses and management recommendations including biological control options (Dougoud et al., this issue).

In other countries, web-based tools for pest identification and management aimed at farmers and growers are becoming commonplace. An example in New Zealand is AgPest, an on-line tool for farmers which allows them to identify pests and weeds that occur in pasture, obtain information on the biology of the pest and weed, and advice on management including biological control (AgPest 2016). This is a freely available website, and farmers can register for free pest forecasts and alerts tailored to their interests and region of the country. Another important on-line tool is the IOBC database on side-effects of pesticides. This database allows farmers to quickly check which pesticides they can use in combination with the natural enemies they have released (https://www.iobc-wprs.org/ip_ipm/IOBC_Pesticide_Side_Effect_Database.html).

Cost-effectiveness of biocontrol

Biological control practitioners are often not effective in demonstrating the financial and other benefits of their programmes. There are two issues. Firstly at the political level the lack of demonstrated cost-effectiveness of biocontrol programmes has not encouraged governments to invest in biocontrol research and development and this in turn has led to reduced interest from academics to carry out research or educate students in biological control. Secondly, at the grower level, farmers and land managers who have not been well engaged in the biocontrol or IPM programmes implemented on their production systems may see only slow progress or no initial impact on pests and feel that it is not providing financial benefits to them compared with pesticides that seem more reliable and predictable.

While it is clear to see how some of these issues might be resolved, a concerted and unified effort from leaders in biological control such as CABI, IOBC and major research organisations and academic institutions might encourage and facilitate economic analyses to be carried out and published as an outcome from the programme. To date relatively few assessments of economic benefits of biological control have been carried out despite the fact that it is probably unsurpassed in providing returns on investment in IPM (Naranjo et al. 2015). These authors, using data from BIOCAT (Greathead and Greathead 1992) argued that historically the benefits that have accrued from the classical biological control programmes that have succeeded are likely to have more than compensated for those that failed. It has been claimed that the benefit:cost ratio for classical biocontrol is 250:1 compared with the costs of developing a successful pesticide, where the final benefit:cost ratio has been calculated as between 2 and 5:1 (Bale et al. 2008). The latter authors noted that the benefit:cost ratios for augmentative biological control were lower, and similar to insecticides, but with very much lower development costs.

A recent analysis carried out in New Zealand for biological control of *Sitona obsoletus* Gmelin (Coleoptera: Curculionidae), the clover root weevil, by the braconid parasitoid *Microctonus aethiopoides* Loan (Hymenoptera: Braconidae) has shown that return on NZ$8.3 million invested in exploration, research and introduction of the parasitoid has been NZ$489 million since 2006, and that by 2018 it will be returning NZ$157 million per annum. The assumptions behind this annual return are that farmers will continue to rely on clover for nitrogen-fixation (reduced by the pest larvae feeding on root nodules), and that the current level of biological control remains stable (Hardwick et al. 2016).

The Australian Weed Management Cooperative Research Centre produced a report on the economic impacts of weed biocontrol programmes against 45 target weeds (Page and Lacey 2006). Almost half resulted in an economic benefit, with an average benefit:cost ratio of 23:1. Amongst these were some outstanding successes where the benefit:cost ratios were over 100:1. In a comprehensive and unique study in South Africa, de Lange and van Wilgen (2010) quantified the benefits of weed biological control against functionally analogous groupings of invasive alien plant species expressed as monetary savings and benefits that accrued to ecosystem services at a landscape (biome) scale. Their estimates of the benefit:cost ratios of weed biological control ranged from 50:1 for invasive sub-tropical shrubs, to >3000:1 in the case of the biological control of invasive Australian trees. These estimated benefits remained strongly positive even when the sensitivity analyses used were very conservative.

Our recommendation is for biocontrol practitioners to involve economists, social scientists and stakeholders early in a biocontrol or IPM programme so that the desired social, economic and environmental benefits can be defined and data can be collected in such a way that their assessments can be effectively and efficiently completed. This will help to clearly and more comprehensively demonstrate the social, environmental and financial value to producers and other stakeholders, and encourage uptake.

Research approach

Much biocontrol research and application has tended to be single crop or individual pest focussed, and so represents a bottom-up process. We suggest that there may be advantages to be gained from taking a more holistic or ecological top-down approach. Rather than considering how we might control a particular pest, the formative question could be: how do we maintain food security in a well-functioning biosphere? While this paper is not the place for a review of sustainable agriculture, there might be enormous benefits from taking a multi-disciplinary approach to research where biological control is just one facet of producing healthy food, or maintaining natural ecosystem function and ecosystem services. This is an area of increasing interest to researchers, and there is considerable effort going into improving our understanding of the relationship between biodiversity, ecosystem function and ecosystem services. The economic benefit from ecosystem services associated with biological control provided by naturally occurring predators, parasitoids and pathogens has been estimated to be vast (Power 2010). This area of conservation biological control involves manipulating or managing agricultural or natural ecosystems in such a way that existing natural enemies are enhanced and resourced to benefit the survival of natural enemies (Landis et al. 2000). Kean et al. (2003) concluded that targeting the most important aspects of natural enemy ecology would most benefit successful conservation biological control. Heimpel and Mills (2017) noted that there are essentially two approaches to enhancement of natural enemy efficacy, manipulation of the habitat to benefit natural enemies at the expense of pests (e.g. increasing resources, habitat quality), and the reduction of impacts of pesticides to natural enemies (e.g. more selective chemicals, improved spatial and temporal use of pesticides). The potential for conservation biological control in developing countries has also been emphasized (Wyckhuys et al. 2013).

Population genetics research presents opportunities to better understand how the impact of biological control can be optimised. For classical biological control, the introduction of agents with wide genetic diversity is clearly likely to assist in adaptation in a new environment (see Wright and Bennett 2017). More suited perhaps to augmentative biocontrol, recent developments like CRISPR gene editing can provide the opportunity to reduce less desirable traits in biological control agents (flight, diapause) and allow for the insertion of new desirable traits such as insecticide resistance (Gurr and You 2016). 'BINGO' (Breeding Invertebrates for Next Generation Biocontrol Control) is an initiative that seeks to improve production and performance of biocontrol agents using state of the art genomic techniques (Pannebakker and Beukeboom 2016).

Biological control is practised in general to bring about a reduction in pest populations below economic thresholds. The point has been made many times that measuring parasitoid attack rates, or percent parasitism does not provide information about population impact (Barlow et al. 2004; van Driesche et al. 1991; Barratt 2011). In some cases a 90% attack rate for a pest species that is *r*-selected (highly fecund but low survival of offspring) will be ineffective. Similarly, in weed biocontrol, records of the establishment and increases in numbers of the herbivorous agents, and of their feeding-impacts on the target host, do not necessarily signal success. Only measures of the effects of the agents on the populations of the target plant (changes in density and distributional range), which are difficult, often take decades, and are exacerbated by complications of seed dynamics and seed stores, can make the definitive case for success achieved with biocontrol (Hoffmann and Moran 1998; Moran and Hoffmann 2012).

Pre-emptive biocontrol to improve the speed at which a biological control agent could be deployed should the arrival of a new pest be considered likely could to some extent 'fast-track' a biocontrol programme. In New Zealand the biosecurity intelligence and border interceptions have indicated the potential for pests likely to present economic and/or environmental risk to New Zealand such as the hemipterans *Homalodisca vitripennis* (Germar) (glassy-winged sharpshooter) (Hemiptera: Cicadellidae) and *Halyomorpha halys* Stål (Hemiptera: Pentatomidae) (brown marmorated stink bug) to arrive in New Zealand. Research to predict the potential distribution (Charles and Logan 2013) or the impact of such pests (Charles 2015) can be very beneficial, and even risk assessment conducted in quarantine in advance of the arrival of the pest (Charles et al. 2016) has the potential to hasten the regulatory process should the need arise.

Basic biological research particularly in the fields of taxonomy, ecology and behaviour, has strongly contributed to the improvement of procedures used in biological control agent exploration, selection and risk assessment. Also, because of studies in the field of population dynamics, population genetics and modelling, we now have a good general understanding of how biological control functions. We believe, however, that there is enormous scope for more cost-effective biocontrol research and implementation to be derived from better collaboration between fundamental and applied scientists.

Fragmentation of effort

Research on biological control of weeds, insects and pathogens have been conducted, deliberately or by default, in isolation of each other with little cross-fertilisation of ideas. There are separate conferences for weed and insect biocontrol: the International Symposium for the Biological Control of Weeds (ISBCW), which has been meeting every four years since 1969, and the International Symposium for

Biological Control of Arthropods (ISBCA), a more recent initiative, which held its first meeting in 2002. Research on biological control of plant diseases has gained momentum over the last 35 years or so (Nicot et al. 2011) and there are now a number of commercially available pathogen-biocontrol agents (see van Lenteren et al. 2017). IOBC-WPRS has a working group on 'Biological and Integrated Control of Plant Pathogens' which is the main forum for researchers in Europe in this aspect of biological control. It has been pointed out that while the science of plant disease biocontrol is gaining in momentum (Brodeur et al. 2017), social acceptance of microbial products is poor, and public education is required. In addition, registration procedures for microbial products is relatively complex, extremely slow and expensive, partly because of lack of expertise of regulators (J. Kohl pers. comm.). Closer integration of biological control practitioners in this area with the wider biological control community might help to overcome some of the barriers which seem to impede more rapid progress and adoption of plant disease management. Biological control of insect vectors of human diseases (e.g. mosquitos) is a specialised sub-discipline of biocontrol science, and given the likely spread of insect-borne diseases with climate change, this should probably achieve better integration with the wider field (see Thomas, this issue).

While weed biocontrol is represented in the IOBC in the membership and by working groups, a well-integrated biocontrol community has never been achieved. There is a view from weed biocontrol researchers that risk aversion and negative perceptions about biological control of insects has hampered progress in weed biocontrol, and, partly for this reason, a decision was made at the 1992 ISBCW that weed biocontrol meetings should not be affiliated to the IOBC (Moran and Hoffmann 2015). However, this position seems to be changing, with an acceptance now that there is a great deal to be gained from closer association between the sub-disciplines of biological control. This can be achieved and indeed facilitated by the IOBC. Occasional combined conferences, shared newsletters and even a conference series that covers the whole field of biological control might be means by which a more unified approach to biocontrol can be fostered. As a result, exposure to researchers working in less familiar systems might result in new insights and approaches, and even collaborations. It was confirmed in early 2017 that an international conference on biological control, covering all aspects, would be planned for 2018 in Beijing, China.

Discussion

Recognition by some of the world's leading agricultural economies that pesticide use needs to be reduced, and/or used more sustainably bodes well for the future of funding for biological control research and its implementation. Although there is almost never enough funding, this is something that could possibly be resolved, or at least alleviated only by raising the profile of biological control globally. Funding agencies need to be convinced of the value (financial, environmental, social and cultural) of investment in biological control research.

In augmentative biological control, the situation has changed in the last five years from a dip in uptake of biocontrol around the year 2000 (van Lenteren 2012) to much improved adoption (van Lenteren et al. 2017). This has come about by political developments in Europe and Asia, and also in Latin America. Demands of retailers and consumers, and actions by NGOs have helped to instigate this change. Furthermore, there are grounds for optimism that political change will in the future be instrumental in increasing availability of funds for research in biological control. Political leaders around the world are recognising the need to reduce pesticide use for the benefit of human well-being. In South Africa, over 20 years ago, the Bill of Rights stated that people have the right to sufficient water, and from that the 'Working for Water' programme has invested considerable funds in biological control of weeds to reduce the risk they pose to water supply (Moran et al. 2005). In Australia, the much reduced research effort in weed biological control seems set to improve, coupled with the recognition by the Convention on Biological Diversity that weed biological control is an acceptable and effective management tool with which to combat invasive plant species (Sheppard and Genovesi 2016).

In emerging countries such as Brazil, biological control research and implementation is gaining momentum for both augmentative and classical biocontrol. In Brazil, the increasing educational opportunities in entomology training in recent decades has resulted in the widespread successful use of biological control (Parra 2014). Significantly, half of the sugarcane crop of Brazil (about 4 M ha) is subject to pest management using biological control programmes using either insects or pathogens. The growing export markets for food products in Brazil is contributing to the need to reduce chemical residues in products (Parra 2014).

China and India are also countries that have invested widely in biological control research, training and adoption. China, for example, has recognised that pesticides and fertilizers have created serious damage to ecosystems and created food security issues and, as a result, the use of agri-chemicals will be capped from 2020. A national research programme on reducing chemical pesticides and fertilizers in China was launched in 2015 (The Economic Times 2015). Two billion Yuan (>US$340 million) will be invested in this programme, which should mean that opportunities for biological control researchers and their international collaborators will result from this.

In the European Union, the Sustainable Use of pesticides Directive 2009 came into force starting in 2011. It was stated "by 26 November 2012 Member States will have to communicate their National Action Plans (NAPs) which will include the description of the measures for implementation […] of the directive to achieve the objectives to reduce risks and to encourage development and introduction of Integrated Pest Management (IPM) and alternative techniques to reduce dependency on the use of pesticides." (European Commission Health and Consumers Directorate General 2011). After nearly a decade of prevarication, ocassioned by bureaucratic and regulatory issues, weed biocontrol in Europe has recently made historic progress with the release of insect agents (Shaw et al. 2011, 2016; Marchante et al. 2011; Shaw and Hatcher 2017) and a pathogen species (Tanner et al. 2015) against some prominent weed species in Europe. These initiatives and developments would seem to herald every prospect for increased funding for biological control and IPM research in the future and the IOBC is set to play an important implementation and facilitating role in the renaissance and development of biocontrol worldwide.

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