4 Economic Value of Arthropod Biological Control

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Integrated pest management (IPM) is the strategic integration of multiple control tactics resulting in the amelioration of pest damage that takes into consideration environmental safety, and the reduction of risk and favourable economic outcomes for growers and society at large. For thousands of years, natural enemies of pests have been harnessed for crop protection (Simmonds *et al.*, 1976). Maximizing this source of natural control is a foundational element in IPM for suppressing the growth of incipient pest populations (Stern *et al.*, 1959). Biological control has been defined as the purposeful use of natural enemies, such as predators, parasitoids and pathogens, to regulate another organism's populations to lower than average levels (DeBach, 1974). Recent and broader perspectives of biological control stress the inclusion of direct and indirect ecological interactions that result in the suppression of target organisms causing harm to humans or their resources (Heimpel and Mills, 2017).

Three broad approaches to biological control are generally recognized. Introductory (classical) biological control primarily focuses on exotic pest species and attempts to provide permanent management of pests by introducing natural enemies from the native region of the pest (DeBach, 1964). These introductions endeavour to re-establish upper trophic level links that effectively suppress the pest species in its native environment. Although the probabilities of success for this approach to biological control are very low, successful programmes have resulted in essentially permanent pest control with very favourable economic outcomes (Cock *et al.*, 2015; Naranjo *et al.*, 2015).

A second approach – augmentative biological control – involves the initial (inoculation) or repeated (inundation) introduction of native or exotic natural enemies to suppress pest populations. Augmentative biological control has been widely and successfully deployed in many parts of the world. It is perhaps most well known in protected agricultural production, particularly in Europe and in developing regions such as China, India and Latin America (van Lenteren *et al.*, 2017). The commercial industry built around this approach to pest control validates its economic viability in some production systems and regions of the world.

Finally, conservation biological control involves manipulation of the environment in such a way that the suppressive forces of resident natural enemies on pest populations are maximized. Conservation biological control may broadly include tactics that lessen negative impacts on resident natural enemy populations resulting from insecticide applications or involve precise engineering of the agricultural environment to encourage the presence, abundance and activity of natural enemies (Barbosa, 1998; Landis *et al.*, 2000). The few studies available suggest that conservation biological control has the potential to provide significant economic value in

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crop protection. Natural biological control, as the name implies, happens independent of any intentional intervention and often operates silently in the background without notice. It is largely the foundation of conservation biological control. That only a tiny fraction of all arthropods are pests is, in part, due in large measure to natural biological control (DeBach, 1974). Broad estimates show that natural control provided through biological control services (trophic regulation of populations) is valued at \$619/ha across multiple biomes (all values in 2018 US\$; Costanza *et al.*, 1997) with biological control in croplands estimated at \$36/ha (Pimentel *et al.*, 1997). Further estimates suggest that natural biological control of native USA crop pests is valued at about \$5.95 billion (Losey and Vaughan, 2006). Some evidence suggests this is a very conservative estimate, as the value of biological control of a single pest of soybean (*Glycine max*) in four Midwestern US states has been valued at \$280 million annually (Landis *et al.*, 2008). Overall, biological control potentially provides among the highest returns on investment available in IPM even while estimation of its economic value has received relatively little attention from entomologists, ecologists or economists (Naranjo *et al.*, 2015).

The economic value of biological control, and general approaches for its estimation, have been discussed and summarized in several excellent reviews (Headley, 1985; Carlson, 1988; Tisdell, 1990; McFadyen, 1998; Gutierrez *et al.*, 1999; Perkins and Garcia, 1999; Hill and Greathead, 2000; Cullen *et al.*, 2008; Waterfield and Zilberman, 2012; Naranjo *et al.*, 2015). A central tenet in IPM is that pest management strategies should provide for economically efficient and sustainable solutions (Chapters 1 and 9). Thus, a better understanding of the economic contribution of biological control, as a foundational element of IPM, will help strengthen adoption of this tactic for IPM more generally, and raise its stock among stakeholders and those that invest in this technology both privately and publicly. The goal of this chapter is to build upon the review of Naranjo *et al.* (2015) by providing more detail on the concepts and methodologies of economic valuation in biological control, to summarize all known projects that have attempted to quantify the economic value of arthropod biological control (with particular focus on introductory and conservation biological control), and to ask how we balance the need for more routine and inclusive economic evaluations with the additional effort needed to spur greater adoption and investment in research and implementation.

Concepts and Methods

Approaches to studying the economic impacts of biological control can vary by their scale and scope. Farm-level studies are often concerned with whether it would be profitable for farmers to adopt biological control practices. Studies at a commodity scale or larger regional scale consider whether producers as a group might benefit from biological control programmes and how benefits are divided among sellers and buyers of agricultural commodities. More comprehensive benefit–cost analyses consider, for example, the return on public investments in larger-scale adoption of conservation biological control or implementation of introductory biological control programmes. The number and types of benefits and costs estimated differ. Farm-level studies often narrowly focus on farm profits, while more comprehensive benefit–cost analyses may consider a wider array of environmental (and other social) benefits and costs. Estimation methods and data requirements also vary by scale and scope.

Measuring farm-level impacts

Farm-level studies often narrowly focus on how adoption of biological control practices affect measures of farm profitability, while ignoring broader economic impacts at larger market scales or economic valuations of environmental impacts. Despite the narrow focus on farm profits, such information is critical. Growers are ultimately the ones making choices about whether or not to implement biological control programmes, either individually on their own farms or through participation in more regional programmes like introductory biological control. Practices that are not profitable stand little chance of being adopted or financially supported by growers. Estimates of farm-level benefits are important precursors to successful extension programmes aimed at encouraging adoption of biological control methods.

A common method of estimating farm-level impacts of biological control is the partial budgeting approach. Here, farm revenues and costs are reported, usually on a per hectare basis. For example, revenues and costs are compared across farms or experimental plots adopting biological control versus those following more conventional practices.

Gross revenues are primarily affected via changes in yields, although the quality or grade of production could affect revenues through changes in prices that growers receive. The costs considered can vary. Some approaches only compare differences in direct insecticide costs (e.g. costs of materials and application). Other factors such as production costs (e.g. for labour, other inputs) might also change.

The partial budgeting approach has been the workhorse of most of the extant studies attempting to value biological control (see below). One reason for this is that data requirements are relatively modest. Only data on observed crop yields, market prices (either actual prices received or regional averages) and costs of production inputs per hectare are needed. If biological control is successful, then these changes in crop yield and insecticide use can be thought of as avoided costs enabled by biological control. Results can be presented in the most basic of business accounting terms that are easy to interpret without any reliance on complex economic methods or theory.

Measuring market-level impacts

Market-level analyses expand the scope of the questions that may be addressed. For example, they may consider how widespread implementation of biological control might affect production across a large class of commodity producers over a regional scale. Because these studies consider effects on entire markets and not just on individuals, effects on commodity prices are important considerations. One can consider how producers as a group are affected. Successful biological control can increase yields, reduce input costs or both. This may lead to an expansion of agricultural production sales. While growers may benefit from lower costs and higher sales volumes, this increased supply can also drive down the market prices they receive. Thus, methods are needed to estimate the relative size of these positive and negative effects. Market-level studies can also assess how consumers are affected by supply shifts. Here, 'consumers' are often 'first purchasers' of farm commodities (i.e. dairies, feedlots or wholesalers) rather than final retail consumers. Consumers defined in this way benefit from greater supplies and lower prices for the agricultural commodities they directly purchase.

While the economic surplus method is a standard analysis for economists, its application to estimate gross benefits of biological control adoption or implementation is relatively rare (White *et al.*, 1995; Lubulwa and McMeniman, 1997; Waterhouse *et al.*, 1999; Macharia *et al.*, 2005; Oleke *et al.*, 2013, Myrick *et al.*, 2014; Letourneau *et al.*, 2015; Zhang *et al.*, 2018). The approach can be conceptualized with a simple, single-commodity supply and demand model (Fig. 4.1A). The *x*-axis is the physical quantity of output (e.g. kg) and the

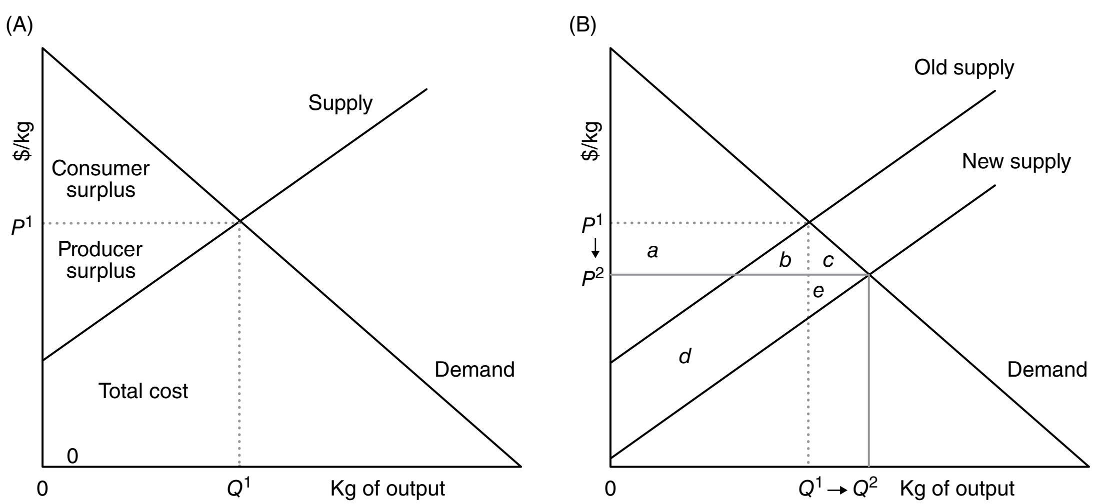

Fig. 4.1. (A) A general economic surplus model defining consumer, producer, and total cost. (B) The addition of successful biological control shifts the supply curve to the right. Consumer surplus increases by the sum of $a + b + c$ because they can purchase more of the good, and at a lower price. Producer surplus rises by $d + e$ because more of the good is sold and costs fall, but falls by area a because producers receive a lower price. The gross gain in total surplus (consumer plus producer surplus gain) from biological control is denoted by $b + c + d + e$.

y-axis is cost or price per unit of output (\$/kg). Areas on the graphic are measured in dollar units (kg × \$/kg = \$). This figure illustrates the solution to a problem of solving for two variables ((i) the physical quantity of a product bought and sold and (ii) the market price of the good), given two equations: one representing consumer demand and the other, producer supply. The demand curve in Fig. 4.1A represents the average revenue producers can obtain by supplying increasing amounts of the good to the market. One may also think of the demand curve as ranking purchasers' willingness to pay for the commodity from highest to lowest. So, with production near the x-axis there are buyers with the highest willingness to pay for the commodity. As more is available, the average amount purchasers are willing to pay falls. Hence the demand curve slopes downward. More can be sold – all else equal – only by reducing price. The supply curve represents the incremental (or marginal) cost of producing one more unit of the good. In Fig. 4.1A, the supply curve slopes upward, which seems intuitive for crop production. To increase production, growers must attempt to get higher yields on limited hectares, for example by purchasing more inputs or expanding production to less productive land. This would increase the costs per unit of output. The market price signals to producers how much they earn from selling an additional unit of the crop, while the supply curve determines how much it will cost producers to supply that additional unit.

The market is in equilibrium (i.e. producers and consumers do not want to change behaviour) where the supply and demand curves intersect. That is, where the quantity bought and sold is Q^1 at price P^1. In market equilibrium, the market price, P^1, is at the level where the quantity demanded (determined by the demand curve) exactly equals the amount that producers are willing and able to sell (determined by the supply curve). At P^1, all demands for the crop are met with no over- or under-supply.

Certain areas in Fig. 4.1A define fundamental economic outcomes. For example, the area under the demand curve between 0 and Q^1 represents the total amount consumers are willing to pay for Q^1 units of the crop, and total sales revenues are $P^1 \times Q^1$ – the product of price received per unit and units sold. The area below the demand curve and above the price line P^1 represents consumer surplus. This is the net benefit purchasers derive (measured in monetary terms) of consuming Q^1. It is the difference between what they would be willing to pay for Q^1 units of the crop and what they actually pay. The area under the supply curve between 0 and the equilibrium quantity produced, Q^1, represents the total cost of producing those Q^1 units. Producer surplus (total profits) is the area below the price line P^1 and above the supply curve. This is also total revenue ($P^1 \times Q^1$) minus total costs. In this simple framework, total benefits to society are just the sum of producer and consumer surplus.

Now suppose a biological control programme reduces the costs of producing a given amount of crop, increases yields or a combination of both. This will have the effect of shifting the supply curve for the commodity outward (Fig. 4.1B). At any given price, producers are willing and able to supply more of the crop. This does two things: (i) more of the crop is produced and sold (an increase from Q^1 to Q^2) and (ii) because there is more supply on the market, the price of the crop falls from P^1 to P^2. For consumers (first purchasers) of the crop, there is more to consume and it can be had at a lower price. The benefits to purchasers (the increase in consumer surplus) is equal to the area $a + b + c$ (Fig. 4.1B). For producers, there are two effects: (i) they can supply more of the crop at lower cost and have greater sales (which benefits them), but (ii) the price they receive from their crop is lower. The loss from lower prices is represented by area a, while the gain from greater sales at lower costs is shown by area $d + e$. The total increase in economic surplus is the sum of consumer and producer surplus gains and is the area below the demand curve and between the old and new supply curves (area $a + b + c + d + e$). The gross gain in total surplus (consumer plus producer surplus gain) from biological control is denoted by $b + c + d + e$.

To conduct a single-commodity market-level assessment, more data are needed than under the partial budgeting approach. Yet, data requirements are still relatively modest. First, one needs estimates of market price and physical quantity sold of the crop for the region of interest. Usually these data are regularly reported government statistics. Second one needs measures of price elasticities of supply and demand, which measure the percentage change in quantity supplied or demanded in response to a change in price. These are often published as part of peer reviewed agricultural economics publications or as part of cooperative extension studies (Nuckton, 1978; You *et al.*, 1996; Russo *et al.*, 2008). With two elasticity estimates and data on price and quantity, one can construct supply and demand curves (Fig. 4.1). This is simply a matter of solving two linear equations (for demand and supply) for two unknowns (the slope and intercept terms of the supply and demand functions). The resulting single-commodity supply and demand model will be calibrated to actual price and production outcomes and based on empirically estimated (or assumed) elasticity (price responsiveness) parameters.

The most challenging part of analysis is estimating how adoption of biological control shifts the supply curve. This will depend not only on estimated impacts per hectare, but also on the percentage of hectares that implement the biological control programme. Collaboration among entomologists and economists is needed to determine how yields and input use changes, and to translate those changes into supply curve changes. Estimates of yield or cost changes may be obtained from surveys of producers, soliciting expert opinion of scientists, or be based on experimental field trial data. Once physical changes are determined, standard formulae are available for calculating surplus effects if one assumes parallel supply shifts and supply and demand linear curves (Alston *et al*., 1995).

Though more comprehensive than simple partial budgeting studies, market-level analysis is incomplete in two critical respects. First, the analysis above only measures gross benefits of biological control. Yet, biological control programmes are not costless to develop and implement. A critical question for grower groups or public agencies supporting biological programmes is: what are the net benefits of the programme (i.e. benefits minus costs)? Second, biological control programmes may reduce insecticide use and preserve biological diversity and other important environmental aspects. These outcomes may provide economic benefits that are generally missed in standard market-based analyses.

Benefit–cost analysis

A more comprehensive type of assessment is benefit–cost analysis: a formal approach to quantifying benefits and costs of public or private projects, programmes or regulations. It follows a four-step procedure: (i) define the project's geographic scope and time horizon, (ii) characterize and enumerate project inputs and outputs, (iii) estimate benefits and costs of these inputs and outputs, and (iv) compare benefits and costs over a time horizon of interest.

Benefit–cost analysis has typically been applied to evaluating introductory biological control where programmes occur over wide geographic and time scales (e.g. Hill and Greathead, 2000). Many costs of programme development and implementation accrue in early years of the project. These costs include labour and materials costs associated with exploration, importation, quarantine, release and distribution, verification of establishment and sometimes evaluation of efficacy. The flow of benefits will not accrue until implementation is underway, but can continue for many years. Benefits include reductions in pest impacts and foregone expenses for alternate control tactics as well as social benefits derived from the reduced use of insecticides (more on these social benefits below). Successful introductory programmes can generate long-term benefits, often relegating a pest to non-economic status.

Economists apply discounting to evaluate benefits and costs that occur at different points in time. Future benefits and costs receive lower values than current ones to reflect people's time preference. People usually value receiving a given dollar value of a benefit in the present more than receiving the benefit in the future. One metric for evaluating a project is net present value (NPV) defined as follows:

$$\mathrm{NPV} = \sum_{t=1}^{T} (B_t - C_t) / (1 + r)^t \qquad \text{(Eqn 4.1)}$$

Where the evaluation horizon extends from the current year, $t = 1$, to the end of the evaluation horizon, year $t = T$. Benefits in year t are B_t, while costs are C_t. The discount rate, r, may be thought of as a rate of exchange between monetary values in future time periods relative to their current, or present, value.

Use of the real discount rate adjusts the discount factor for inflation, which affects the relative value of current and future money. There is no consensus about any single discount rate to apply (Field and Field, 2006). Practitioners usually use higher rates to compare programmes in terms of the opportunity cost of foregoing alternative private investments. Practitioners more often use lower rates when evaluating government projects providing benefits across long time horizons. The results of applying the NPV formula above can be highly sensitive to assumptions about the discount rate or time horizon as well as the long-term flow of benefits. Sensitivity analyses are typically used to examine how changes in these assumptions affect the NPV of introductory biological control programmes (e.g. White *et al.*, 1995; Lubulwa and McMeniman, 1997; Macharia *et al.*, 2005; Oleke *et al.*, 2013).

Projects may be evaluated in terms of NPV (discounted benefits minus discounted costs), but they are also often reported in terms of the benefit–cost ratio (BCR) (discounted benefits divided by discounted costs):

$$\mathrm{BCR} = \sum_{t=1}^{T} \frac{B_t(1+r)^{-t}}{C_t(1+r)^{-t}} \qquad \text{(Eqn 4.2)}$$

The BCR will exceed 1 for any project with positive net (discounted) benefits. The BCR is a common metric in economic evaluations of introductory biological control (see below) and as noted, sensitivity analyses are frequently conducted to assess the robustness of the outcome to assumed values of certain parameters, for example, the discount rate. Such sensitivity analysis is important if there is uncertainty about the values parameters may take. A simple hypothetical programme (Fig. 4.2) exemplifies how the selection of the discount rate and the time horizon over which benefits are expected to accrue can affect the outcome. As the discount rate rises, the cumulative benefits of the programme over time decline. This will also affect the BCR. In this example, with a discount rate of 10% the BCR never exceeds 1. With smaller discount rates, BCR values >1 are possible but depend on how long the benefits accrue. Even with a discount rate of 3% a favourable BCR only arises after nearly 20 years. These examples point to the importance of sensitivity analyses, especially in cases where the ultimate BCR may be only slightly larger than unity.

Another metric is the internal rate of return (IRR) (Napit *et al.*, 1988) given by the formula:

$$0 = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+\mathrm{IRR})^{t}} \qquad \text{(Eqn 4.3)}$$

The IRR is the interest rate that, if applied, would make the project NPV equal zero. It represents a ‘break-even’ rate of return on an investment, showing the highest rate of interest for which the project shows neither a profit nor a loss. One may compare the IRR to an investor’s cost of capital to determine whether a proposed project is acceptable. If the IRR is greater than rates of interest charged for borrowing for capital investments, it would suggest that a project is economically justifiable. Similarly, one might compare the IRR of a project to rates of returns to government treasury securities or stock market rates of return. This metric is not often estimated in economic analyses of biological control but could be useful in determining if certain projects should be undertaken. For example, Aidoo *et al.* (2016) estimated an IRR of 1740% under a worse-case scenario for biological control of cassava green mite in Ghana, suggesting the programme was clearly worth the investment.

Externalities – non-market benefits and costs

In addition to comparing the flow of benefits and costs across time, benefit–cost analysis may consider social benefits and costs in addition to purely private benefits and costs. External benefits or costs can be generated by pest management decisions that accrue to others that are not directly involved in an economic transaction. Common examples of these externalities in agricultural crop protection include long-term effects on worker health, effects on water quality, effects on biodiversity or other ecological effects. These external effects (either benefits or costs) represent true benefits or costs to society even if they are not reflected in costs or prices resulting from private market activity. As such, a comprehensive benefit–cost analysis should include the full social costs and benefits (private as well as external costs and benefits) of a programme. One implication of externalities is that if growers cannot capture the external benefits of biological control they may underadopt those practices. Likewise, if growers do not bear all the external costs of pesticide use, they may tend to overuse pesticides from a social perspective. Estimating externalities of insecticide use within the context of biological control are extremely rare. One example comes from a study to estimate the biological control value of bats in cotton production. Cleveland *et al.* (2006) estimated the environmental cost of insecticides for *Helicoverpa zea* in cotton (*Gossypium hirsutum*) at $34/kg of active ingredient (2018 US$) based on aggregate estimates of the social and environmental cost of pesticides from Pimentel *et al.* (1991) and pesticide use estimates for the USA (Gianessi and Anderson, 1995).

Overall, externalities lead to divergence between private profitability and collective economic welfare. Positive or negative externalities can be imposed by one grower on another. Thus, the effects of biological

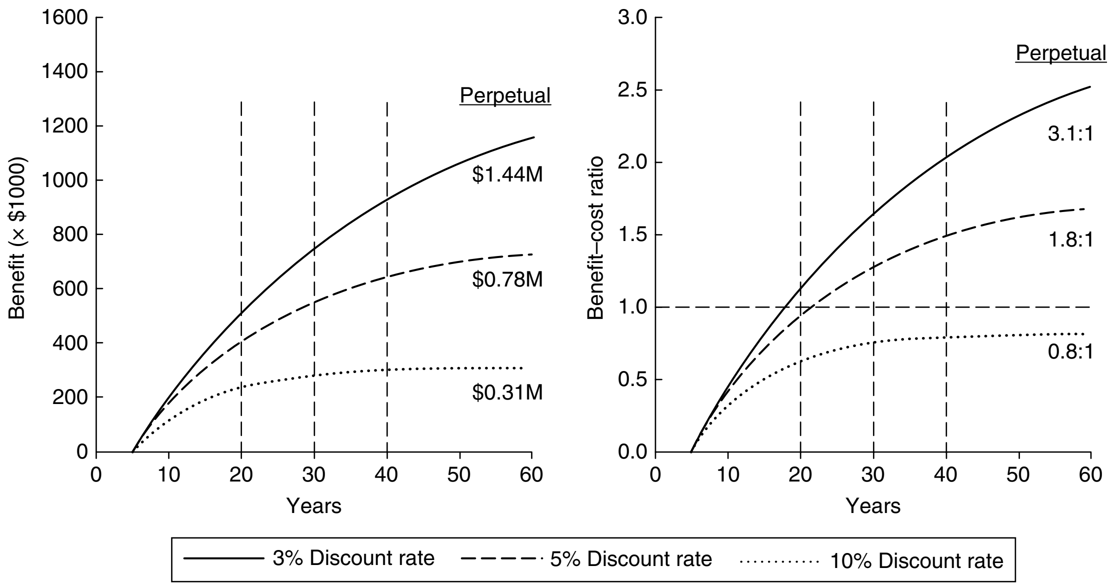

Fig. 4.2. Hypothetical case in which the benefits are $50,000 annually after the fifth year and the cost of the programme is $100,000 annually for the first 5 years. The example shows how the discount rate of money and the time horizon used to estimate benefits affect the outcome in terms of benefit–cost ratios, and why sensitivity analyses are required in documenting impact. Perpetual estimates illustrate how the discount rate eventually causes benefits and benefit–cost ratios to plateau.

control should be assessed on growers as a group. For example, the application of insecticides by one grower could negatively affect regional populations of natural enemies that might be important for managing pests in a neighbouring crop (e.g. Grogan and Goodhue, 2012). Growers that collectively adopt biological control could potentially delay the evolution of insecticide resistance in pests. Thus, biological control, in contributing to pest suppression might postpone the evolution and eventual cost of pest resistance through limiting or delaying insecticide applications (e.g. Liu *et al*., 2012). Given the costs of insecticide development (Sparks and Lorsbach, 2017), it seems feasible to quantify the impacts of biological control in extending the duration and efficacy of certain insecticides. It also might be possible to estimate effects of biological control on other ecosystems services like pollination (e.g. Morandin *et al*., 2016).

One potential method to assess non-market benefits of biological control is the contingent valuation method (CVM). CVM is a direct, survey-based method to elicit people's willingness to pay for a non-market benefit or to avoid some risk. CVM questionnaires first identify and describe some environmental resource or risk and ask respondents to consider a hypothetical change in the resource or risk (Carson, 2000; Field and Field, 2006). Surveyors pose a series of questions designed to elicit respondents' willingness to pay to bring about or avoid the change. CVM has the potential to measure benefits people derive that do not involve depleting a resource (called passive use or non-use values). One such value is existence value – the value that people might attach to the existence of a species and the loss they would feel as a result of the species' extinction (Carson, 2000; Field and Field, 2006).

While CVM has been applied in hundreds of studies measuring environmental benefits (Carson, 2000, 2012), the method is controversial (Hausman, 2012; Kling *et al*., 2012; Haab *et al*., 2013). CVM can lead to biased and unreliable responses because it poses hypothetical questions that do not require respondents to make actual economic choices (Field and Field, 2006; Hausman, 2012). While some economists argue that carefully designed applications can provide reliable results (Carson, 2000, 2012), others have raised doubts about CVM's ability to generate reliable and consistent measures of people's willingness to pay to obtain non-market benefits or avoid non-market costs (Hausman, 2012). To inform debates over the validity of CVM-based estimates of environmental values, the US National Oceanographic and Atmospheric Administration (NOAA) formed a panel of experts chaired by two Nobel Laureates in economics. The NOAA panel concluded that CVM 'produces estimates reliable enough to be the starting point of a judicial process of damage assessment, including passive-use values' (Arrow *et al.*, 1993, p. 4610). The panel also provided a detailed set of recommended practices to enhance the validity of survey results.

Applications of CVM assessing values of biological control have been limited to date. One such study surveyed local residents about their willingness to pay for different methods of protecting urban shrubs and trees. Respondents were willing to pay over 20 times more for a biological control compared with an insecticide option (Jetter and Paine, 2004). In another study of Indian farmers, respondents reported they would be willing to pay 33% more for insecticides that were safer for beneficial insects (Singh *et al.*, 2007). An *ex-ante* study of farmers in Niger assessed their willingness to pay for beneficial insects (Guerci *et al.*, 2018). Cuyno (1997) found that onion (*Allium cepa*) growers in the Philippines were willing to pay $14.50 per crop season to reduce insecticide risks to beneficial insects. Finally, a study of Washington apple (*Malus pumila*) and pear (*Pyrus* sp.) growers found that respondents stated a willingness to pay $74/ha in apples and $111/ha in pears (2018 US$) for insecticides with lower toxicity to natural enemies (Gallardo and Wang, 2013).

Introductory (Classical) Biological Control

Introductory biological control has a long history in pest control that continues to be a key tool in the management of exotic arthropod pests. The project that many practictioners consider to have formally initiated the science of introductory biological control (and of biological control generally – hence the often used moniker 'classical') was the introduction and establishment of *Rodolia cardinalis* and *Cryptochaetum iceryae* against the cottony-cushion scale (*Icerya puchasi*), an invasive pest of citrus in California, in the late 19th century. This introduction has successfully controlled this pest for more than a century. A recent update of a long-standing database (BIOCAT, Greathead and Greathead, 1992) that attempts to catalogue all introductory biological control projects against arthropod pests globally estimates there have been 6158 introductions against 588 pest species in 148 countries as of 2010 (Cock *et al.*, 2016). Analysis of this database further estimates that of the extant projects, 32.6% have resulted in the establishment of exotic natural enemies (primarily arthropods) and that about 10% of all introductions have resulted in at least satisfactory control of 172 pest arthropods (Cock *et al.*, 2016). While this rate of success may seem very low, some perspective can be provided via the agro-chemical industry. It is estimated that nearly 160,000 insecticidal compounds must be screened to identify one viable enough to take to market (0.0004%; Sparks and Lorsbach, 2016). Further, the average cost and time to develop and register that one compound in the US is $286 million and >10 years, respectively (Sparks and Lorsbach, 2016) with an estimated BCR of 2:1–5:1 (Bale *et al.*, 2008).

One of the first attempts to estimate the economic value of the resulting pest control did not occur until at least 1930 (Table 4.1), despite the long history of introductory biological control and the significant positive impacts that successful projects can entail. In this project, a hymenopteran parasitoid (*Coccophagus gurneyi*) was used to successfully control the citrophilus mealybug (*Pseudococcus fragilis*) in California citrus orchards. For an investment of about $24,000 (constant 2018 US$), more than $172 million was saved in yield loss and insecticide costs over a 30-year time horizon for an estimated BCR of >7000. In our search of the literature through 2018, we were able to document another 43 projects in which some degree of economic analyses were completed, the most recent in 2013 (Table 4.1). The BIOCAT database (Cock *et al.*, 2016) lists the vast majority of these projects as providing substantial and complete pest control. Even the few that provided only partial control still provided positive economic benefits (Table 4.1). Based on 6158 introductions, this equates to <1% of all projects that have been formally assessed economically. In parallel, it has been noted (Hill and Greathead, 2000; Heimpel and Mills, 2017) that many introductory programmes also have not been rigorously

Table 4.1. Summary of economic evaluations conducted for introductory biological control programmes targeting arthropod pests.

Crop	Pest	Natural enemy	Country (year)	Cost US$ (2018) × 1000[ab]	Benefit US$ (2018) × 1000[ab]	Benefit:cost ratio	NPV	Discount rate %[c]	Horizon years[c]	Method[†]	Metric(s)	Programme outcome (BIOCAT database)[d‡]	Citation
Field crops													
Sugarcane	*Diatraea saccharalis*	*Lixophaga diatraea*, *Metagonistylum minense*	Antigua (1931)	194.3	3,556.0	18.3	3,361.7	10	30	PB	Avoided crop loss value	P	(1), (2), updated from (3)
			St. Kitts (1934)	4.6	10,775.8	2356.7	10,771.2	10	30	PB	Avoided crop loss value	S/C	(1), (2), updated from (3)
			St. Lucia (1933)	22.9	2,586.2	113.1	2,563.4	10	30	PB	Avoided crop loss value	S/C	(1), (2), updated from (3)
Alfalfa	*Therioaphis maculata*	*Aphelinus asychis*, *Praon exsoletum*, *Trioxys complanatus*	USA (1958)	6118.8	222,715.4	36.4	216,596.5	10	30 (10)	PB	Avoided crop loss value?	S/C	(3), updated from (4)
Sugarcane	*Diatraea saccharalis*	*Lixophaga diatraea*, *Metagonistylum minense*, *Apanteles flavipes*	Barbados (1967)	881.5	55,396.0	62.8	54,514.6	10	30	PB	Avoided crop loss value	S/C	(5), updated from (3)
Maize	*Mythimna seperata*	*Apanteles ruficrus*	New Zealand (1974)	116.5	604,037.2	5184.8	603,920.7	10	30	PB	Avoided crop loss value	C	(6), updated from (7)
Sugarcane	*Aulacaspis tegalensis*	*Lindorus laphanthae*	Tanzania (1971)	60.8	13,220.3	217.3	13,159.4	10	30	PB	Avoided crop loss value	C	(6), updated from (7)
Cassava	*Phenacoccus manihoti*	*Apoanagyrus lopezi*	Africa* (1977)	49,513.9	7,379,618.4	149.0	7,330,104.5	10	30 (25)	PB	Avoided crop loss value, partial *ex-ante*	S	(8), updated from (7)
			Africa* (1979)	38,677.6	5,942,460.2	153.6	5,903,782.5	10 (6)	30 (40)	PB	Avoided crop loss value; no imports	S	(9)
			Africa* (1979)	38,677.6	12,347,448.9	319.2	12,308,771.3	10 (6)	30 (40)	PB	Avoided crop loss value; cost of import to offset losses	S	(9)
Forage/lawn grass	*Antonina graminis*	*Neodusmetia sangwani*	USA (1978)	628.6	5,268,080.7	8,381.1	5,267,452.2	10	30	PB	Avoided cattle/ urban turf loss value	C	(10), updated from (7)

Continued

Table 4.1. Continued.

Crop	Pest	Natural enemy	Country (year)	Cost US$ (2018) × 1000[ab]	Benefit US$ (2018) × 1000[ab]	Benefit:cost ratio	NPV	Discount rate %[c]	Horizon years[c]	Method[†]	Metric(s)	Programme outcome (BIOCAT database)[d‡]	Citation
Alfalfa	*Hypera postica*	Various parasitoids	USA (1987)	53,175.3	1,274,024.6	24.0	1,220,849.3	10 (4)	30 (16)	ESM	Avoided crop loss value; avoided insecticide costs	S	(11), (12), updated from (7)
Cereals	*Metopolophium dirhodum*	*Aphidius rhopalosiphi*	New Zealand (1988)	1,627.0	3,485.9	2.1	1,858.8	10	30	PB	Avoided crop loss value (survey)	S	(13), updated from (7)
				1,627.0	58,097.8	35.7	56,470.8						
Maize	*Chilo partellus*	*Cotesia flavipes*	Kenya (1991)	18,421.5	587,542.4	31.9	569,120.9	10	30 (20)	PB	Avoided crop loss value	P/S	(14)
Cassava	*Mononychellus tanajoa*	*Typhlodromalus manihoti*	Ghana (2008)	37.6	301.5	8.0	263.9	10 (20)	30 (40)	PB	Avoided crop loss value	N/A	(15)
Pasture (for cattle)	*Neoscapteriscus spp.*	*Larra bicolor*, *Ormia depleta*, *Steinernema scapterisci*	USA (2013)	9,314.6	152,614.0	16.4	143,299.4	10 (3)	30 (perpetual)	PB	Avoided insecticide costs	S	(16)
Vegetables/fruits/nut crops													
Citrus	*Pseudococcus fragilis*	*Coccophagus gurneyi*	USA (1930)	23.8	172,248.6	7,244.6	172,224.8	10	30 (10)	PB	Avoided crop loss value; avoided insecticide costs	S	(3), updated from (4)
Coffee	*Planococcus kenyae*	*Anagyrus* spp.	Kenya (1939)	685.9	107,758.2	157.1	107,072.4	10	30 (10)	PB	Avoided crop loss value?	S	updated from (3)
Grapes	*Harrisinia metallica*	*Sturmia harrisinae*, *Apanteles harrisinae*	USA (1945)	8458.9	28,570.4	3.4	20,111.6	10	30 (10)	PB	Avoided crop loss value?	N/A	(3), updated from (4)
Coconut	*Aspidiotus destructor*	*Cryptognatha nodiceps*	Principe (1955)	74.5	11,420.6	153.3	11,346.1	10	30	PB	Avoided crop loss value?	C	(2), updated from (3)
Olive	*Parlatoria oleae*	*Aphytis maculicornis*, *Coccophagoides utilis*	USA (1962)	1,469.3	37,691.6	25.7	36,222.3	10	30 (10)	PB	Avoided crop loss value?	C[e]	(3), updated from (4)
Citrus	*Icerya purchasi*	*Rodalia cardinalis*	Caribbean (1966)	43.8	399.9	9.1	356.1	10	30	PB	Avoided insecticide costs	S	(2), updated from (7)
Coconut	*Promecotheca cumingi*	*Dimmockia javana*	Sri Lanka (1971)	243.6	25,962.0	106.6	25,718.4	10	30	PB	Avoided crop loss value	C	(6), (17), updated from (7)
Potato	*Phthorimaea operculella*	*Copidosoma koehleri*	Zambia (1972)	179.0	4,209.1	23.5	4,030.1	10	30	PB	Avoided crop loss value	S	(6), updated from (7)

Citrus	*Ceroplastes destructor*	*Anicetus communis*, *Paraceraptrocerus nyasicus*	Australia (1976)	4,498.5	6,254.6	1.4	1,756.1	10	30	PB	Avoided insecticide costs	P	(18), (19), updated from (7)
Deciduous fruit	*Tetranychus urticae*	*Galendromus occidentalis*	Australia (1976)	2,552.0	60,057.2	23.5	57,505.2	10	30	PB	Avoided insecticide costs	N/A	(18), (19), updated from (7)
Citrus	*Selenaspidus articulatus*	*Aphylis roseni*	Peru (1977)	6.0	5,791.0	963.5	5,785.0	10	30	PB	Avoided insecticide costs	C	(6), updated from (7)
Coconut	*Brontispa longissima*	*Asecodes* sp.	Western Samoa (1981)	1,688.8	29,971.0	17.7	28,282.2	10 (8)	30 (10)	PB	Avoided crop loss value	S	(20), updated from (7)
Filberts	*Myzocallis coryli*	*Trioxys pallidus*	USA (1985)	57.5	4,205.6	73.1	4,148.1	10	30	PB	Avoided insecticide costs	P	(21)
Mango, citrus	*Rastrococcus invadens*	*Gyranusoidea tebygi*	Togo (1986)	272.1	219,857.0	808.1	219,585.0	10	30	PB	Avoided crop loss value	S	(22), updated from (7)
Mango	*Rastrococcus invadens*	*Gyranusoidea tebygi*, *Anagyrus mangicola*	Benin (1988)	6,891.6	1,062,424.1	154.2	1,055,532.5	10	30 (20)	PB	Avoided crop loss value	S	(23)
Banana	*Erionata thrax*	*Cotesia erionotae*	Papua New Guinea/ Australia (1990)	353.6	21,916.7	62.0	21,563.1	10 (8)	30	ESM	Avoided crop loss value	S	(24), updated from (7)
			(1990)	581.9	113,530.2	195.1	112,948.3	10 (5)	30	ESM	Avoided crop loss value	S	(25)
Breadfruit	*Icerya aegyptiaca*	*Rodolia limbata*	Kiribati, Micronesia, Marshall Islands, Palau (1990)	805.6	2,675.4	3.3	1,869.8	10 (8)	30	ESM	Avoided crop loss value	S	(24), updated from (7)
Tropical/ subtropical fruit	*Eudocima fullonia*	*Ooencyrtus* sp., *Ooencyrtus crassulus*, *Telenomus* sp.	Fiji, Western Samoa, Tonga (1990)	913.6	701.8	0.8	–201.8	10 (8)	30	ESM	Avoided crop loss value	P/C	(24) updated from (7)
Citrus	*Aleurocanthus spiniferus*	*Encarsia smithi*	Swaziland (1995)	47.4	1,250.1	26.4	1,202.7	10 (0)	30 (1)	PB	Avoided crop loss value; avoided insecticide costs	P	(26)
Cabbage	*Plutella xylostella*	*Diadegma semiclausum*, *Anagyrus* sp. nr. *kivuensis*	Kenya (1999)	1,728.6	43,464.1	25.1	41,735.5	10	30 (25)	ESM	Avoided crop loss value, avoided control costs	S	(27)

Continued

Table 4.1. Continued.

Crop	Pest	Natural enemy	Country (year)	Cost US$ (2018) × 1000[ab]	Benefit US$ (2018) × 1000[ab]	Benefit:cost ratio	NPV	Discount rate %[c]	Horizon years[c]	Method[†]	Metric(s)	Programme outcome (BIOCAT database)[d‡]	Citation
Coconut	*Aceria guerreronis*	*Neoseiulus baraki*, *N. paspalivorus*, *Proctolaelaps bickleyi*	Benin (2008)	167.0	316.6	1.9	149.6	10 (12)	30 (20)	ESM, *ex-ante*	Avoided crop loss value	N/A	(28)
Papaya, mulberry, cassava, tomato, aubergine	*Paracoccus marginatus*	*Acerophagus papayae*	India (2010)	515.2	9,213,920.7	17,885.2	9,213,405.5	10 (5)	30 (5)	ESM	Avoided crop loss value, avoided insecticide costs	N/A	(29)
Forests/ornamental trees													
Spruce trees	*Gilpinia hercyniae*	Variable	Canada (1932)	2,519.2	61,573.6	24.4	59,054.4	10	30	PB	Avoided crop loss value	S	(30), updated from (7)
Oak forests	*Operophtera brumata*	*Cyzenis albicans*, *Agrypon flaveolatum*	Nova Scotia (1971)	2,708.3	30,710.1	11.3	28,001.8	10	30	PB	Avoided lumber loss value	P/S	(6), updated from (7)
Pine trees	*Sirex noctilio*	Variable	Australia (1979)	15,659.1	38,471.6	2.5	22,812.4	10	40	PB	Avoided crop loss value (40 year production cycle)	P	(18), (19), updated from (7)
Ornamental ash/pear	*Siphoninus phillyreae*	*Encarsia inaron*	USA (1990)	2,133.9	564,984.0	264.8	562,850.1	N/A	N/A	PB	Avoided wholesale tree replacement	S	(31)
				2,133.9	522,905.2	245.1	520,771.4	N/A	N/A	PB	Avoided retail tree replacement	S	(32)
				2,133.9	385,252.7	180.5	383,118.8	N/A	N/A	PB	Avoided wholesale tree replacement	S	
Eucalyptus	*Ctenarytaina eucalypti*	*Psyllaephagus pilosus*	USA (1992)	101.6	2,321.3	22.8	2,219.7	10 (8)	30 (15)	PB	Avoided insecticide costs	C	(33)
				101.6	4,678.7	46.0	4,577.1	10 (8)	30 (15)	PB	Avoided insecticide costs		

Eucalyptus	8 pest species (Coleoptera, Hemiptera)	7 species (Hymenoptera)	USA (1992)	4,364.2	4,668,376.9	1,069.7	4,664,012.7	N/A	N/A	PB	Avoided retail tree replacement	P/C	(34)
				4,364.2	1,867,891.5	428.0	1,863,527.3						
Ornamental trees	*Gonipterus scutellatus*	*Anaphes nitens*	USA (1994)	0.0	0.77/citizen		N/A	N/A	N/A	CV	Avoided retail tree replacement	S	(35)
Eucalyptus	*Gonipterus platensis*	*Anaphes nitens*	Portugal (1997)	1,877.6	4,040,290.8	2,151.9	4,038,413.2	10 (4)	30 (20)	PB	Avoided insecticide costs	N/A	(36)
				1,877.6	4,253,173.6	2,265.3	4,251,296.0			PB	Avoided retail tree replacement	N/A	
				1,877.6	14,601,516.9	7,776.8	14,599,639.3			PB	Avoided import costs	N/A	

[a]All figures in 2018 constant US$ (gross domestic product: implicit price deflator, http://research.stlouisfed.org/fred2/series/GDPDEF/); data prior to 1947 were converted using the implicit price deflator for 1947.
[b]Currencies converted to US$ using https://data.oecd.org/conversion/exchange-rates.htm#indicator-chart; conversions prior to 1950 used conversion factor for 1950.
[c]Discount rates and horizon years were standardized to 10% and 30 years where possible using data provided by study authors; original study rates and years indicated in parentheses. N/A = not applicable.
[d]Cock *et al.*, 2016; N/A = not available in database.
[e]Noted as C by Huffaker *et al.*, 1976, but no control in the BIOCAT database.
*27 different countries in Africa.
†PB – partial budgeting; CV – contingent valuation; ESM – economic surplus model.
‡P – partial control; C – complete control; S – substantial control.

References: (1) Box, 1960; (2) Simmonds, 1967; (3) Huffaker *et al.*, 1976; (4) Gutierrez *et al.*, 1999; (5) Alam *et al.*, 1971; (6) CAB, 1980; (7) Hill and Greathead, 2000; (8) Norgaard, 1988; (9) Zeddies *et al.*, 2001; (10) Dean *et al.*, 1979; (11) White *et al.*, 1995; (12) Bryan *et al.*, 1993; (13) Grundy, 1990; (14) Kipkoech *et al.*, 2006; (15) Aidoo *et al.*, 2016; (16) Mhina *et al.*, 2016; (17) Dharmadikari *et al.*, 1977; (18) Marsden *et al.*, 1980; (19) Tisdell, 1990; (20) Voegele, 1989; (21) Aliniazee, 1995; (22) Voegele *et al.*, 1991; (23) Bokonon-Ganta *et al.*, 2002; (24) Lubulwa and McMeniman, 1997; (25) Waterhouse *et al.*, 1999; (26) Van den Berg *et al.*, 2000; (27) Macharia *et al.*, 2005; (28) Oleke *et al.*, 2013; (29) Myrick *et al.*, 2014; (30) Reeks and Cameron, 1971; (31) Jetter *et al.*, 1997; (32) Pickett *et al.*, 1996; (33) Dahlsten *et al.*, 1998; (34) Paine *et al.*, 2015; (35) Jetter and Paine, 2004; (36) Valente *et al.*, 2018.

assessed from a technical and ecological perspective. This situation is not unique to arthropod biological control but also applies to weed biological control (McFadyen, 1998).

There are several possible reasons why economic outcomes have not been formally measured in more introductory biological control programmes. First, such programmes are almost exclusively carried out by publicly funded institutions for the benefit of agriculture and society more generally. Once the invasive organism has been relegated to non-pest status, the economic benefit to the grower and to society is obvious and perhaps not worthy of additional effort to quantify. Furthermore, the BCRs are so high for the successful programmes assessed that perhaps there is diminished incentive to invest further in economic analyses. Second, introductory biological control programmes are complex and involve long time horizons with numerous interrelated steps needed to achieve success (DeBach, 1964; Hokkanen, 1985; van Driesche and Hoddle, 2000). Often, the final phases of the programme that involve evaluation of ecological, sociological and economic outcomes suffer from lack of funding, personnel and perhaps even scientific interest, as the project wraps up and has met its goal of pest suppression (McEvoy and Coombs, 1999; van Driesche and Hoddle, 2000; Heimpel and Mills, 2017). Third, it is only relatively recently that economists have taken a fuller interest in assessing introductory programmes. Many of the early economic evaluations were done ad hoc by entomologists (e.g. DeBach, 1964; Simmonds, 1967), with little attention paid to standard economic approaches such as economic surplus modelling and use of discount rates to properly value the dollars spent or earned in the past (Hill and Greathead, 2000). However, the paucity of economic evaluations belies the important need for them to be completed. As noted above, knowing the economic value of introductory biological control could pay dividends in terms of strengthening support for its utility in battling invasive pests and providing incentive among stakeholders, policy makers and legislators that control regulatory processes and funding needed to advance the technology. Public funds for research and implementation are being scrutinized more and more, and there is increased emphasis on evaluating the outcomes of arthropod management projects funded by public grants (Naranjo *et al.*, 2015).

The record of evaluations

A search of the literature through to mid-2018 resulted in the identification of at least 44 projects that have been subject to some level of economic valuation and where the specific contribution of biological control could be assessed (Table 4.1). Several reviews have summarized the extant data and attempted to standardize discount rates for the changing value of money over time, and the time horizon over which the benefits have accrued (Gutierrez *et al.*, 1999; Hill and Greathead, 2000). Here we expand on these summaries by attempting to place all known valuations on a standard platform of 30-year time horizons with a 10% discount rate, and converting all US and foreign currencies to constant 2018 US$. This standardization then allows us to further speculate on trends due to time, the types of crops and other factors. Often, study authors provided sufficient data to make the time horizon and discount rate conversion relatively easy. However, in some case where time horizons were less than 30 years, we had to use a bit of scientific licence to extrapolate benefits beyond the data provided in the studies. Typically, this was done by averaging the benefits over the reported years or simply continuing the fixed benefits per year reported by study authors. Because successful introductory biological control is most often associated with permanent pest control after initial introduction and establishment of agents (DeBach, 1964; Huffaker *et al.*, 1976), this is a reasonable and perhaps conservative approach. As noted above, no one seems to agree on the best discount rate to use in economic analyses. Thus, a discount rate of 10% was chosen to represent a conservative approach.

The few projects that have been assessed economically represent a diversity of crops, pests, natural enemies and regions of the world. The cases summarized include over 50 target pest species attacking 32 crops in more than 50 countries. By comparison, BIOCAT catalogues 588 pest species in 148 countries (crop type was not reported; Greathead and Greathead, 1992; Cock *et al.*, 2016). Several studies on the cassava mealybug included assessments from multiple African nations (Norgaard, 1988; Zeddies *et al.*, 2001). The vast majority of the natural enemies were hymenopteran parasitoids, followed distantly by dipteran parasitoids and coleopteran predators. The greatest period of activity for economic evaluations appears to have been between 1970 and 2000, with moderate activity between

1930 and 1940 and little activity from 1940–1970 and since 2000. In large measure, this drop in activity coincides with reduced introductions and reduced rates of success overall (Cock *et al.*, 2016). One could speculate that biological control activity during these periods was associated with post-World War II development of synthetic insecticides and perhaps the changing regulatory environment, respectively. Given the small sample size of evaluated projects, it is not possible to quantitatively compare proportional effort relative to all projects globally, but the diversity of taxa and regions would suggest that these examples could perhaps provide insight into overall patterns in outcomes.

Economic values vary widely for evaluated programmes (Table 4.1). The cost of programmes (all values in 2018 US$) varied from as little as $4600 to introduce and establish two dipteran parasitoids for control of *Diatraea saccharalis* on sugarcane (*Saccharum*) in St. Kitts (Box, 1960; Simmonds, 1967) to >$53 million to introduce and establish multiple parasitoids for control of *Hypera postica* on alfalfa (*Medicago sativa*) in multiple US states (Bryan *et al.*, 1993; White *et al.*, 1995). The benefit of pest control in St. Kitts was valued at >$10.7 million for a BCR >2300, while in the USA, control of *Hypera postica* yielded a benefit of >$1.2 billion for a BCR of 24. These two cases illustrate both the differential impact of regional scope and the advantage of expanding upon a recent programme. The success in the small island of St. Kitts followed from the introduction of this same agent in another Caribbean nation several years earlier, thus driving down programme costs substantially, particularly those associated with exploration. In contrast, the alfalfa programme covered multiple US states and millions of hectares and involved multiple research organizations and biological control agents. The introduction of a hymenopteran parasitoid for control of *Paracoccus marginatus* on multiple, relatively high-value crops in India resulted in an estimated benefit of over $9 billion for a cost of just over $500,000, with a BCR of nearly 18,000 (Myrick *et al.*, 2014). In contrast, biological control of the tropical fruit pest, *Eudocima fullonia*, in Fiji, Western Samoa and Tonga cost over $900,000 and resulted in benefits of only $700,000 for a BCR <1 (Lubulwa and McMeniman, 1997). For all 44 projects, the geometric mean of benefits and costs were $38.16 million and $621,670, respectively, with a BCR of just over 61. The geometric mean was used, because it more accurately represented the central tendency of the log-normal distribution of the data over all projects (Table 4.1). By contrast, the arithmetic mean and median BCR were 1099 and 32, respectively.

Economic approaches and outcomes

While the economic surplus model is a standard approach favoured by economists (see above), we found very few examples using this methodology. In the vast majority of cases partial budgeting was used in which the value of biological control was measured simply by the avoided loss of crop yield, the avoided cost of insecticides that biological control enabled or both, without taking into consideration the elasticity of crop supply or consumer demand relative to the outcome of biological control. Some notable exceptions include the evaluation of a large alfalfa project in the USA (White *et al.*, 1995) and projects associated with a variety of vegetable, fruit and nut crops in Australasia, the Pacific Island region, India and Africa (Lubulwa and McMeniman, 1997; Waterhouse *et al.*, 1999; Macharia *et al.*, 2005; Oleke *et al.*, 2013; Myrick *et al.*, 2014).

Based on avoided costs of yield loss, one might expect larger values in higher-value crops, such as vegetables and fruits, to yield relatively larger benefits and perhaps more favourable BCRs. However, this was not the case for the data available. Instead, these crops had the lowest NPV (NPV = discounted benefits – discounted costs over 30 years) and the lowest BCRs even though estimated NPVs and BCRs were still substantial. Field crops had the highest BCR, while forest and ornamental tree projects had the largest NPV (Table 4.1, Fig. 4.3). Although field crops have an inherently lower value per hectare, the larger scale under which these crops are produced results in a greater aggregate value of biological control. Thus, what these analyses show is that the estimation of the economic value of biological control is multifaceted and dependent on several factors, including the geographic scope of the project, the degree of control, the standard of living and crop values in the countries involved, and the time when the projects were initiated. There is a slight trend for the cost of programmes to increase with time. While relatively inexpensive programmes can be seen throughout the time course of the database, the more expensive projects were found during the 1970s, 1980s and 1990s. In turn, these years also yielded the projects

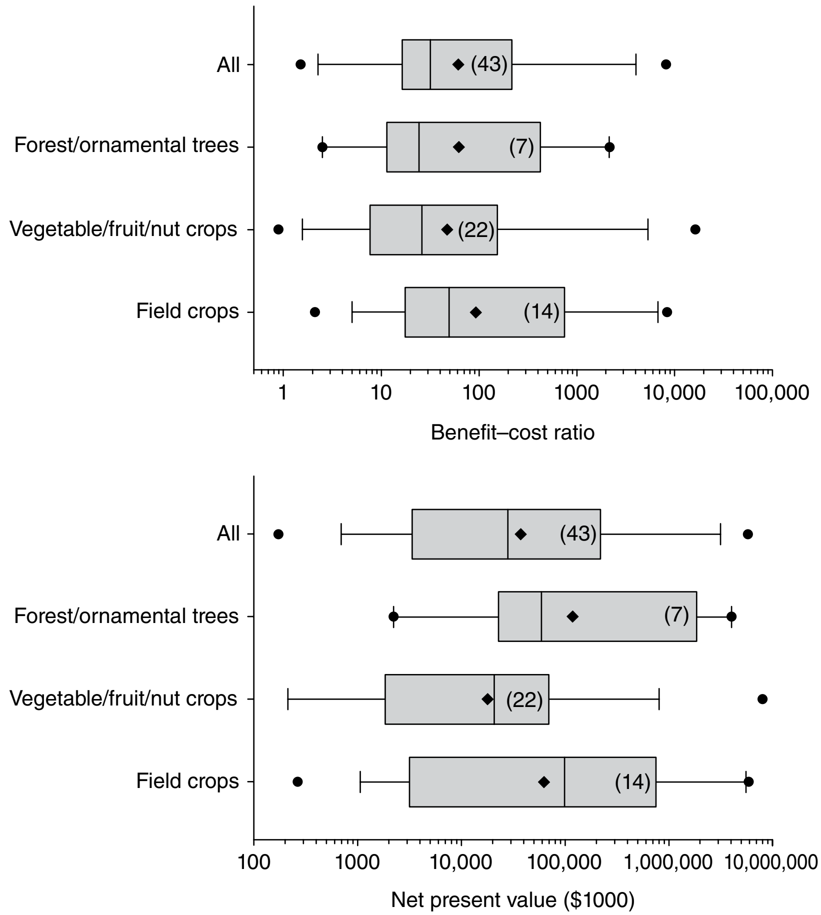

Fig. 4.3. Summary of benefit–cost ratios and net present values (NPV) for introductory biological control projects from 1930–2013. For box plots, the line within each box represents the median, the box bounds the 25th and 75th percentiles, the whiskers denote the 10th and 90th percentiles, round points denote 5th and 95th percentiles, and the diamonds within bars denote the geometric mean. Sample sizes are shown in parentheses. In cases where a range of estimates were provided in a study, the lowest estimate was used; data from Table 4.1. All values in constant 2018 US$.

with the largest benefits and NPV. These high costs and high NPV were associated with large-scale programmes in the USA (Dean *et al.*, 1979; White *et al.*, 1995), 27 African countries (Norgaard, 1988; Zeddies *et al.*, 2001; Kipkoech *et al.*, 2006), Australia (Marsden *et al.*, 1980; Tisdell, 1990), India (Myrick *et al.*, 2014) and Portugal (Valente *et al.*, 2018). Increasing regulations and new agreements on benefits sharing have changed the environment for introductory biological control (Cock *et al.*, 2009, 2016). It remains unclear what impacts these factors might have on the costs, but it is likely these factors have impacted the development and implementation of new projects. What the record clearly shows is that even using a fairly conservative discount rate of 10% that BCRs are still larger than 1, and in many cases, much larger than 1. To put this in context, most of us would be happy to realize a BCR of anything even slightly >1 in our personal investments.

As noted above, the full benefits of biological control cannot be measured by focusing simply on partial budgeting approaches such as avoided crop losses and insecticide costs (e.g. Simmonds, 1967; Huffaker *et al.*, 1976; Tisdell, 1990; Hill and Greathead, 2000). Insecticide use can have long-term effects on such things as worker health, water and soil quality, and other ecological parameters. These external costs are not captured in the simple analyses completed to date for biological control in general. Their inclusion would undoubtedly increase the value of biological control even more. There are also broader social and economic benefits that are recognized but rarely captured. For example, a recent study on introductory biological control of cassava mealybug in Thailand suggests that successful control of the pest not only had positive benefits for growers in the region, but also may have had a cascading positive influence in stabilizing the dynamics of the cassava starch markets in Asia and globally (Wyckhuys *et al.*, 2018b). Conversely, introductory biological control is not without risks, such as unintended non-target effects (van Driesche and Hoddle, 2016), and a complete accounting of benefits and costs also should consider these externalities.

The record of introductory biological control clearly represents a good investment of public dollars for those projects that have been successful and have been economically evaluated. However, questions sometimes arise regarding the economic viability of the overall introductory approach. That is, have those successful projects, or even those projects that have been economically evaluated, represented a positive gain for the enterprise in general? Some suggest that the successes have paid for the failures (e.g. Hill and Greathead, 2000) but to our knowledge no one has ever tried to quantitatively test this assumption. Based on 43 projects (one project used contingent valuation and did not estimate net costs or benefits) that estimated costs and benefits of introductory biological control programmes, the sum of NPVs is $31.58 billion (2018 US$), the known net value of all programmes for which we have data (or a geometric mean of $37.35 million per project). In instances where several studies examined the same programme or where multiple estimates were made for a given programme based on different avoided cost assumptions, we chose the smallest and most conservative estimates of NPV. The average cost (measured as the geometric mean) of these 43 programmes was $621,670. If we first assume that these 43 projects are representative of the roughly 620 successful cases of biological control (the 10% success rate of Cock *et al.*, 2016), then that leaves 5538 (6158 – 620) failures. Conservatively then, the estimated average cost of each failure would have to be about $5.70 million to break even with all dollars spent on introductory biological control ($31.58 billion/5538). This represents the 83rd percentile of all known costs (Table 4.1). More conservatively, if we assume that these projects are representative of all the projects that have not been economically evaluated (6158 – 43), then the average cost of each 'failure' would have to be about $5.16 million to break even, or the 82nd percentile of all known costs. The mole cricket biological control programme in Florida is the most recent project evaluated and estimated costs were about $9.3 million (Mhina *et al.*, 2016). Costs for other programmes since 2000 ranged from $37,600–515,200 (Table 4.1). It seems reasonable to conclude that successes in introductory biological control are likely to have more than paid for failures and this would be even more certain if we had NPV estimates for all 620 successes.

Augmentative Biological Control

Augmentative biological control encompasses a range of approaches to enhancing pest control. At one end of the spectrum is inoculation biological control in which agents are introduced, for example, at specific times during a particular phase of the crop or pest dynamics. The goal is to seed an area with natural enemies that can then become self-sustaining over the season or multiple seasons. In inundation, natural enemies are released, sometimes in large numbers and sometimes repeatedly to achieve quick suppression of the pest. Inundation biological control is most often associated with microbial agents but can also be true of parasitoids and predators depending on the application (Heimpel and Mills, 2017). In practice, augmentation can fall anywhere between these extremes of inoculation to inundation biological control.

Unlike introductory biological control, which is basically a publicly funded enterprise, augmentation is primarily a privately funded, for-profit endeavour. The size and scope of the augmentative biological control industry suggests that this approach to biological control is thriving in certain regions of the world, particularly in Europe, where policies and public investment incentivize the use of non-chemical options (van Lenteren *et al.*, 2017). As of 2016, it is estimated that about 350 species of natural enemies (predators, parasitoids and pathogens) are available commercially from around 500 suppliers globally. Many of these are small operations with <10 employees but there are several large companies employing upwards of 1400 people. Recent data estimate the size of the industry at about \$1.7 billion annually with about a 15% rate of growth since 2005 (van Lenteren *et al.*, 2017) and an overall BCR of around 2:1 to 5:1 (Bale *et al.*, 2008; Pilkington *et al.*, 2010; van Lenteren, 2012). There are also government-funded rearing facilities in regions such as China, India and Latin America (van Lenteren and Bueno, 2003; Wang *et al.*, 2014) and some private, large-grower operations in Latin America (van Lenteren *et al.*, 2017). In California, for example, a grower-owned cooperative rears and sells several species of predators and parasitoids, at cost, for mostly fruit and vegetable crops, and has been in operation since 1928 (Associates Insectary; www.associatesinsectary.com).

Despite the size of the augmentative biological control industry and government sponsorship of mass-rearing programmes, there are probably fewer examples of studies that have directly assessed the economic benefits of this form of biological control, compared with introductory and even conservation approaches. Certainly, with the volume of sales in the augmentation industry one would predict a solid economic benefit to the technology, but extant studies have provided mixed results. One of the most thorough assessments involved the rearing and release of pesticide-resistant predator mites (*Metaseiulus occidentalis*) for control of *Tetranychus* spp. in almonds, *Prunus dulcis* (Headley and Hoy, 1987). Their *ex-ante* analysis showed that after accounting for the costs of research to develop the programme and for rearing, the BCR ranged from 14:1 to 34:1. Additional assessments also point to positive BCR (Reichelderfer, 1979; Hussey and Scopes, 1985) with values on par with many introductory biological control programmes (Gutierrez *et al.*, 1999). Other programmes have shown positive net returns equal to those provided by insecticides (Moreno and Luck, 1992) or lower than those provided by insecticides but still better than no control at all (Trumble and Morse, 1993; Olson *et al.*, 1996). Still other programmes have shown that augmentative releases were more expensive than the standard use of insecticides to provide the same level of control (Lv *et al.*, 2011, and summarized in Collier and Van Steenwyk, 2004). The integration of augmentation with insecticides or biopesticides in an IPM programme has yielded positive net gains for systems such as cotton (Liapis and Moffitt, 1983), soybean (Greene *et al.*, 1985), tomato, *Solanum lycopersicum* (Trumble and Alverado-Rodriguez, 1993), mango, *Mangifera indica* (Peng and Christian, 2005) and maize, *Zea mays* (Gardner *et al.*, 2011). A recent *ex-ante* study from Niger (Guerci *et al.*, 2018) suggests that the development of an augmentation industry may be viable for control of a millet pest if production costs are kept low and there is a threshold level of demand in farming villages. In protected agricultural systems where augmentation is considered more viable (van Lenteren *et al.*, 2017), the results of economic analyses have been mixed. Sometimes augmentation is much more costly than the alternative use of insecticides (Hoddle and van Dreische, 1996, 1999; Stevens *et al.*, 2000; Vasquez *et al.*, 2006), but may offer positive value under organic production systems where insecticide choices are more limited (Garcia *et al.*, 2012).

Conservation Biological Control

Conservation biological control represents perhaps the oldest form of biological pest control and is a foundational element for both introductory and augmentative biological control insomuch that the goal is to enhance survival and activity of introduced agents. Often cited is the example from China over 3000 years ago where farmers manipulated the environment to encourage pest control with weaver ants in citrus (Olkowski and Zhang, 1998). Farmers placed bamboo ladders between trees to facilitate ant movement and dug moats around the bases of the trees to retain the ants. The overall goal of conservation is to provide a habitat more suitable to natural enemies so that they are able to increase in abundance and/or to function better in pest suppression. This goal can be met by removing or attenuating disruptive factors such as insecticides, enhancing the crop and/or bordering habitats, or better utilizing surrounding habitats to provide needed requisites for natural enemy population retention and growth (van den Bosch and Telford, 1964; Barbosa, 1998; Landis *et al.*, 2000). Underpinning conservation biological control is natural biological control, a component of natural control that works in the background without intervention, and largely goes unnoticed in suppressing incipient pest populations (Stern *et al.*, 1959). Without sufficient natural biological control, conservation would not be possible.

The economic framework behind conservation biological control falls somewhere in the middle between introductory and augmentation biological control. Public funding may be provided in the way of research and extension programmes at publicly funded institutions (Naranjo *et al.*, 2015) and in supporting general habitat conservation programmes like those administered by public institutions (Griffiths *et al.*, 2008). There also is private investment by the direct beneficiaries of conservation – the growers. They are the ones who must make the decisions on matters such as insecticide usage and application approaches, use of selective materials and the use of thresholds to optimize timing of insecticide applications so that natural enemies are preserved (e.g. Stern *et al.*, 1959; Croft, 1990). Growers are also the investors in habitat modifications such as planting and maintaining things like flowering borders (Gurr *et al.*, 2004), and in the design of farm landscapes (Thies and Tscharntke, 1999; Griffiths *et al.*, 2008) to increase natural enemy abundance and activity. One also could make the case that the agrochemical industry invests via the development of more selective insecticides and genetically modified crops that allow for more targeted control of pests without the associated disruption of their natural enemies. Thus, there is both public and private investment. As with other forms of biological control, the benefits accrue to growers in terms of enhanced pest control and to the public in terms of increased supplies and reduced prices of agricultural products (see economic surplus discussion above), but also via reductions in environmental and food safety risks.

The record of evaluations

Conservation biological control projects have received much less attention compared with introductory biological control in terms of formal economic analyses; however, some recent work is encouraging (e.g. Colloff *et al.*, 2013; Letourneau *et al.*, 2015; Daniels *et al.*, 2017; Zhang *et al.*, 2018). Although many assessments have worked within a general benefit–cost framework, the cost side of the equation has been less explicit compared with introductory biological control. Thus, many estimates provide either aggregate net benefits, or more commonly, net benefits per unit of crop production ($/ha). A search of the literature identified 36 studies involving the management of arthropod pests with arthropod or vertebrate natural enemies and two additional studies involving the management of vertebrate pests with vertebrate natural enemies (Table 4.2). Most of these studies provided explicit economic outcomes, and in several cases there were sufficient data presented to allow us to estimate economic outcomes using additional data on the cost of insecticides (e.g. Naranjo *et al.*, 2004; Walker *et al.*, 2010; Hallett *et al.*, 2014). Of these 36 studies, 13 can be more accurately classified as examples of natural biological control as they simply measured the economic value of resident natural enemies in cases where there was no intentional intervention (e.g. modified insecticide use, habitat engineering).

The earliest study of which we are aware was the estimation of the economic value of naturally occurring generalist arthropod predators of *Pseudatomoscelis seriatus* in the US cotton system based on a pest–plant simulation model (Sterling *et al.*, 1992). Since that time, studies have been conducted on nearly 40 pest species (plus assessments based on multiple species on a given crop) in 23 crops in 18 countries (Table 4.2). The vast majority of this work has happened since around 2010, perhaps precipitated by the review publications of Cullen *et al.* (2008) and Naranjo *et al.* (2015), both of which made strong cases for the need to conduct research in this area. The vast majority of studies are from the USA, followed distantly by studies from New Zealand, Spain, Indonesia and Jamaica, and single studies from a number of other countries. There also appears to be a larger number of studies on cotton, followed distantly again with studies on a few other crops such as soybean, wheat (*Triticum aestivum*), coffee (*Coffea*), and then one or two studies on a wide range of other field and horticultural crops (Table 4.2). Values of biological control range widely, from zero in several cases in low-value conventional crop production systems (compared with organic; Sandhu *et al.*, 2010) to over $22,000/ha (2018 US$) from a best-case scenario in high-value pear orchards in Belgium (Daniels *et al.*, 2017). Combining all studies, the average (measured as the geometric mean) value of conservation and natural biological control was about $74/ha. It is likely that economic values for conservation and natural biological control could be derived from the data published in other studies that were not identified in our search. Directly comparing the value of conservation and introductory biological control is problematic given the differing approaches, geographic scales and time horizons inherent to each approach. Introductory programmes are more open ended in terms of the affected geographic and temporal scale of the impact. The outcomes of conservation

Table 4.2. Summary of economic value of conservation biological control and natural biological control of arthropod and vertebrate pests.

Crop	Pest species	Country	Natural enemy	CBC value (US$/ha)[a]	Method	Metric(s)	Study type	Reference(s)
Field crops (modify insecticides used, natural enemy-based thresholds)								
Barley	*Rhopalosiphum padi*	Sweden	Ground-dwelling predators	70 (organic), 49 (conventional)	PB	Avoided insecticide costs and crop loss	Experimental and modelling studies	Östman *et al*., 2003
Cotton	*Bemisia tabaci*, *Lygus hesperus*	United States	Generalist predators, parasitoids	99	PB	Avoided insecticide costs	Experimental, selective versus broad-spectrum insecticides; includes other natural control factors	Naranjo *et al*., 2004; Naranjo and Ellsworth, 2009a
Cotton	All arthropod pests	United States	Generalist predators, parasitoids	117	PB	Avoided insecticide costs and crop loss	Willingness to pay; survey of professional pest control advisors in Arizona, USA	Naranjo *et al*., 2015
Cotton	Secondary pests	United States	Generalist predators	17	PB	Avoided insecticide costs	Data mining	Gross and Rosenheim, 2011
Soybean	*Aphis glycines*	Canada	Generalist predators	28	PB	Avoided insecticide costs	Experimental, farm trials	Hallett *et al*., 2014
Soybean	*Aphis glycines*	United States	Generalist predators	5–41	PB	Avoided insecticide costs and crop loss	Data sourcing, modelling	Zhang and Swinton, 2012
Wheat	*Acyrthosiphon pisum*	New Zealand	Ground-dwelling predators	40 (organic), 0 (conventional)	PB	Avoided insecticide costs	Experimental, farm trials	Sandhu *et al*., 2010
Wheat	*Sitobion avenae*	UK	Native predators, parasitoids and pathogens	0 (low infestation), 20 (moderate infestation), 7 (high infestation)	ESM	Avoided crop loss	Experimental, data sourcing	Zhang *et al*., 2018

Field crops (habitat manipulation)								
Cotton	*Helicoverpa armigera*, *Diparopsis watersi*, *Earias huegeli*, *Pectinophora scutigera*, *Nezara viridula*, *Dysdercus sidae*	Benin	Generalist predators, parasitoids	298 (organic)	PB	Avoided crop loss value, cost of food spray	Farm trials with beneficial food sprays	Mensah *et al.*, 2012
Rice	*Nilaparvata lugens*	Thailand, Vietnam, China	Native predators and parasitoids	80	PB	Avoided insecticide costs and crop loss; cost of flowering borders included	Experimental, farm trials	Gurr *et al.*, 2016
Rice	*Chilo supressalis*	Spain	*Soprano pipistrelle* (bats)	30	PB	Avoided insecticide costs	Experimental, farm trials	Puig-Montserrat *et al.*, 2015
Soybean	*Aphis glycines*	United States	Generalist predators	40	PB	Avoided insecticide costs and crop loss	Farm-level trials, experimental exclusion	Landis *et al.*, 2008
Field crops (natural biological control)								
Cotton	*Pseudatomoscelis seriatus*	United States	Generalist predators	29	PB	Avoided crop loss value	Validated insect/plant model	Sterling *et al.*, 1992
Cotton	*Helicoverpa zea*	United States	Free-tailed bats	254	PB	Avoided insecticide costs and crop loss; includes social costs of insecticide	Data sourcing, modelling	Cleveland *et al.*, 2006
Cotton	*Helicoverpa zea*	United States	Free-tailed bats	63–293 (Bt cotton), 117–1038 (non-Bt)	PB	Avoided insecticide costs and crop loss; includes social costs of insecticide	Data sourcing, modelling	Federico *et al.*, 2008

Continued

Table 4.2. Continued.

Crop	Pest species	Country	Natural enemy	CBC value (US$/ha)[a]	Method	Metric(s)	Study type	Reference(s)
Cotton	*Helicoverpa zea*	United States	Free-tailed bats	75 (1990), 16 (2007)	PB	Avoided insecticide costs and crop loss; includes social costs of insecticide	Experimental exclusion	López-Hoffman *et al*., 2014
Cotton	*Aphis gossypii*	China	Generalist predators	11	PB	Avoided insecticide costs and crop loss	Data sourcing, modelling	Huang *et al*., 2018
Maize	*Helicoverpa zea*	United States	Free-tailed bats	8 (non-Bt), 3 (Bt)	PB	Avoided crop loss	Experimental exclusion	Maine and Boyles, 2015
Clover, grass, biomass trees, barley, wheat	*Rhopalosiphum padi*, *Sitobion avenae*, *Metopolophium dirhodum*, *Delia coarctata*	Denmark	Ground-dwelling predators	16 (pasture), 15 (biomass), 0 (cereals)	PB	Avoided insecticide costs	Experimental, farm trials	Porter *et al*., 2009
Vegetable, fruit and nut crops (modify insecticide use, natural enemy-based thresholds)								
Cabbage	*Plutella xylostella*	Nicaragua	Parasitoid, predatory wasps	2,381	PB	Avoided insecticide costs and crop loss	Farm-scale grower practice (calendar sprays), additional unmeasured gains in resistance management noted	Bommarco *et al*., 2011
Carrot	*Psila rosae*	New Zealand	Ground-dwelling predators	54 (organic), 0 (conventional)	PB	Avoided insecticide costs	Experimental, farm trials	Sandhu *et al*., 2010
Apples	Leafrollers, aphids, mites; secondary pests	United States	Native predators and parasitoids	204	PB	Avoided insecticide costs	Experimental, farm trials	Gallardo *et al*., 2016
Pears	*Cacopsylla pyricola*; secondary pest	United States	Native predators and parasitoids	208	PB	Avoided insecticide costs	Experimental, farm trials	Gallardo *et al*., 2016
Apples	Pests in general	United States	Native predators and parasitoids	74	CV		N/A	Gallardo and Wang, 2013

Pears	Pests in general	United States	Native predators and parasitoids	111	CV		n/a	Gallardo and Wang, 2013
Tomato	*Helicoverpa armigera*	New Zealand	Parasitoids	17	PB	Avoided insecticide costs	Farm-level experiment	Walker *et al*., 2010
Vegetable, fruit and nut crops (habitat manipulation)								
Citrus (oranges)	*Pezothrips kellyanus*	Australia	Predatory mites	2,472–7,998	PB	Avoided insecticide costs and crop loss	Farm-level experiment	Colloff *et al*., 2013
Citrus (clementines)	*Tetranychus urticae*	Spain	Predatory mites	380–693	PB	Avoided insecticide costs; ground cover costs included	Experimental, farm trials	Aguilar-Fenollosa *et al*., 2011
Pear	*Cacopsylla pyricola*	Belgium	Generalist predators	3,140–22,810	PB	Avoided crop loss value	Data sourcing, modelling	Daniels *et al*., 2017
Squash/ cucumber	*Anasa tristis*, *Acalymma vittatum*	United States	Native predators and parasitoids	80–802	ESM	Avoided crop loss value	Data sourcing	Letourneau *et al*., 2015
Tomato	*Various tomato pests*	United States	Native predators and parasitoids	–18 (no hedgerow cost sharing), 98 (50% cost sharing)	PB	Avoided insecticide costs	Experimental, data sourcing, modelling	Morandin *et al*., 2016
Vegetable, fruit and nut crops (natural control)								
Cacao	*Conopomorpha cramerella*, *Helopeltis sulawesi*	Indonesia	Ants	992	PB	Avoided crop loss value	Experimental exclusion	Wielgloss *et al*., 2014
Cacao	*Helopeltis sulawesii*, *Conopomorpha cramerella*, Lepidoptera, Coleoptera, Aphididae, Orthoptera, Blattodea	Indonesia	Insectivorous birds/bats	789	PB	Avoided crop loss value	Experimental exclusion	Maas *et al*., 2013

Continued

Table 4.2. Continued.

Crop	Pest species	Country	Natural enemy	CBC value (US$/ha)[a]	Method	Metric(s)	Study type	Reference(s)
Coffee	*Hypothenemus hampei*	Jamaica	Insectivorous birds	372	PB	Avoided crop loss value	Experimental exclusion	Johnson *et al*., 2010
Coffee	*Hypothenemus hampeii*	Costa Rica	Insectivorous birds	83–341	PB	Avoided crop loss value	Experimental exclusion	Karp *et al*., 2013
Coffee	*Hypothenemus hampeii*	Jamaica	Insectivorous birds	54–129	PB	Avoided crop loss value	Experimental exclusion	Kellermann *et al*., 2008
Macadamia	*Nezada viridula*	South Africa	Insectivorous bats	60–146	PB	Avoided insecticide costs and crop loss	Data sourcing, modelling	Taylor *et al*., 2018
Non-arthropod pest examples (habitat manipulation)								
Grapes (Sauvignon Blanc)	Passeriformes birds	New Zealand	Native falcons	269	PB	Avoided crop loss value	Experimental, farm trials	Kross *et al*., 2012
Grapes (Pinot noir)	Passeriformes birds	New Zealand	Native falcons	375	PB	Avoided crop loss value	Experimental, farm trials	Kross *et al*., 2012
Sweet cherries	Fruit-eating birds	United States	Native kestrels	85–192	PB	Avoided crop loss value	Experimental, farm trials	Shave *et al*., 2018

[a]All figures in 2018 constant US$ (gross domestic product: implicit price deflator, http://research.stlouisfed.org/fred2/series/GDPDEF).
*PB – partial budgeting; ESM – economic surplus model; CV – contingent valuations

biological control tend to apply to a specific field or farm within a given season, but they also can have wider benefits if conservation practices such as landscape manipulation are regional. Conservation biological control also might contribute to mitigation of insecticide resistance, which could have broader regional impacts. Such outcomes are less easily measured in conservation due to generally local focus.

Economic approaches and outcomes

Similar to introductory biological control, the extant studies attempting to quantify the economic value of conservation or natural biological control have, with few exception, been based on partial budgeting approaches using avoided loss of crop yield and/or the avoided cost of insecticides without any consideration of the elasticity of crop supply or consumer demand within an economic surplus framework (Table 4.2). Letourneau *et al.* (2015) used an economic surplus approach to estimate the value of biological diversity in biological control of cucurbit pests in the south-eastern USA. They showed that economic values resulting from enhanced crop protection from more diverse natural enemy communities were 85–88% higher compared with the common approach that assumes fixed commodity pricing and loss of value (akin to partial budgeting analysis). They further conclude that an economic surplus approach provides more accurate economic outcomes for both producers and consumers of the commodity. A similar economic surplus approach was used to estimate the value of biological control of *Sitobion avenae* by resident natural enemies on wheat (*Triticum aestivum*) in the UK (Zhang *et al.*, 2018). They suggested that the value of biological control could vary significantly based on the interaction between pest abundance and use of thresholds to time insecticide treatments. The highest average values were associated with moderate pest densities and the use of thresholds because natural enemies were capable of delaying threshold-level pest densities, thus saving insecticide costs and improving yield. They showed no value of biological control when initial pest densities were low, thus eliminating yield reductions and sprays altogether. However, they did not consider that low initial pest densities could have resulted from natural biological control and so its value was likely underestimated. Similar variable economic outcomes, in terms of interactions of pest and natural enemy densities with thresholds, were demonstrated through simulation modelling studies with *Aphis glycines* in the Midwestern USA (Zhang and Swinton, 2012).

The use of an avoided cost metric for estimating economic value of conservation resulted in predictable general outcomes (Table 4.2, Fig. 4.4). The value of conservation biological control in higher-value fruit, vegetable and nut crops was over four times higher compared with lower-value field crops, regardless of whether conservation was enabled by modification of insecticide use or habitat engineering. This differential was even higher for natural biological control between field and horticultural crops. Activities that fostered biological control through habitat engineering or modification of insecticide use also resulted in greater value than natural biological control, especially for control of pests in field crops (Fig. 4.4). This would suggest that the investment in conservation tactics is worthwhile, although some studies did not account for all the associated costs. For example, the deployment of ground covers to enhance biological control of thrips in Australian citrus resulted in some of the largest benefits measured, but the study did not account for the costs of establishing and maintaining the ground covers (Colloff *et al.*, 2013). It also appears that habitat engineering tends to lead to greater economic value in resulting biological control than the modification of insecticide use via avenues such as use of more selective materials and/or deployment of thresholds to guide application decisions (Table 4.2, Fig. 4.4). But again, there may not have been a full accounting of habitat engineering costs. Another factor to consider is that readily available selective insecticides and selective transgenic insecticidal crops are relatively new and perhaps their complete benefits have yet to be realized.

The connection between the market value of a crop and the resulting value of biological control is predictable within an avoided cost context, but this nexus is perhaps an unsatisfying outcome in some circumstances. For example, the biological control services provided by bats on caterpillar pests of cotton was estimated to drop from $75/ha in 1990 to $16/ha in 2007 (Table 4.2) with the wide-scale adoption of transgenic Bt cotton in the US (López-Hoffman *et al.*, 2014). The additional control of caterpillars via highly effective host-plant resistance lessened the value of bats as biological control agents even while the abundance of bats did not

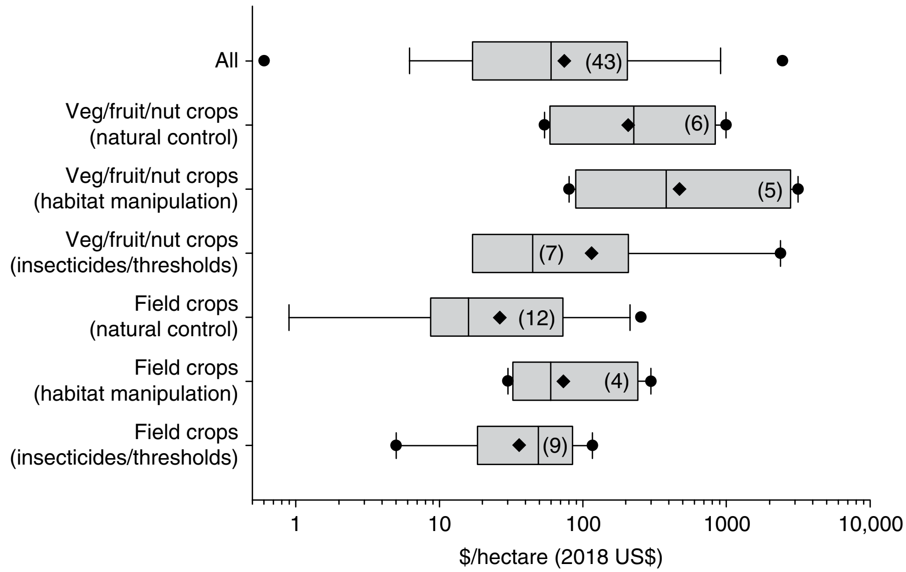

Fig. 4.4. Summary of economic valuations for conservation biological control and natural control of arthropod pests relative to crop type and approach to conservation. Insecticides/thresholds involve studies using selective insecticides and/or biological control based thresholds. Habitat manipulation involves studies using some form of habitat engineering to enhance natural enemy abundance. For box plots, the line within each box represents the median, the box bounds the 25th and 75th percentiles, the whiskers denote the 10th and 90th percentiles, round points denote 5th and 95th percentiles, and diamonds denote the geometric mean. In cases where a range of estimates were provided in a study, the lowest estimate was used; data from Table 4.2.

change. This outcome raised concerns about maintaining interest in conservation programmes for bats more generally. This same phenomenon was noted in comparing Bt and non-Bt cotton. Bat services were much more valuable in non-Bt cotton ($117 – 1038/ha) than in Bt cotton ($63 – 293/ha) because bats killed fewer moths in Bt cotton (Federico *et al.*, 2008). These contextual conundrums perhaps provide incentive for more inclusive measurement of both market and non-market factors when placing a value on biological control.

Modified insecticide use and economic thresholds

Insecticides remain a key tactic in IPM, and 60 years after Stern and colleagues (1959) introduced the integrated control concept we struggle with ways to integrate chemical and biological control for sustainable pest management (but see Furlong *et al.*, 2004; Naranjo and Ellsworth, 2009a, 2009b). Many of the new insecticides introduced every year have reduced spectrums of activity that make them potential fits in IPM programmes. In Arizona cotton (Ellsworth *et al.*, 2011, 2017), we screen almost every new chemistry that becomes available in order to find those that support our long and ongoing cotton IPM programme focused primarily on conserving natural enemies (Naranjo and Ellsworth, 2009b). Based on extensive experimental work to quantify natural enemy induced mortality in *Bemisia tabaci*, to examine the comparative selectivity and efficacy of insecticides and to contemporaneously measure cotton farmers' pest management decisions (Ellsworth *et al.*, 2017), we estimate that conservation biological control is valued at about $100/ha. In simple terms, this is the differential in total cost of broad-spectrum and selective insecticides to achieve the same level of pest suppression. Selective insecticides, while more costly per application, enable biological control, thus leading to fewer sprays. Pest control advisors in Arizona indicate that they value biological control at $117/ha providing independent verification (Naranjo *et al.*, 2015). On a broader scale, we estimate that Arizona growers overall have saved well over $500 million in yield loss and insecticide costs since 1996, with about 25–42% ($130–221 million) of this saving attributed directly to conservation biological control (Ellsworth *et al.*, 2017; Reisig *et al.*, Chapter 9).

The use of techniques like pheromone-based mating disruption can modify insecticide use and provide an environment more conducive to conservation biological control. Studies in the Pacific Northwest of the USA showed that using pheromones for the primary pest (*Cydia pomonella*) reduces the alternate use of broad-spectrum insecticides and consequently enables biological control of secondary pests valued at >$200/ha for apple and pear growers (Gallardo *et al.*, 2016). Organic production systems for barley, wheat, cotton and carrot, in comparison with conventional systems using broader-spectrum insecticides, enable significant biological control valued at $40–298/ha (Östman *et al.*, 2003; Sandhu *et al.*, 2010; Mensah *et al.*, 2012).

The economic injury level (EIL) and the associated economic threshold (ET) are foundational elements of IPM (Stern *et al.*, 1959; Onstad *et al.*, Chapter 7). The EIL is the level of pest density or injury at which the cost of control equals the value of damage prevented, while the ET is the operation level at which control actions are taken to prevent pest densities from exceeding the EIL. With these concepts, economics is implicitly embedded in the decision process of IPM. In turn, biological control can be incorporated into this decision framework to further reduce risks to growers and ultimately enhance economic outcomes (Brown, 1997; Giles *et al.*, 2017). Some work has led to operational plans (Hoffman *et al.*, 1990; Conway *et al.*, 2006; Walker *et al.*, 2010; Hallett *et al.*, 2014; Vandervoet *et al.*, 2018) and several have enabled estimation of the value of conservation biological control (Walker *et al.*, 2010; Zhang and Swinton, 2012; Hallett *et al.*, 2014) via the avoided costs of unneeded insecticide sprays (Table 4.2). Additional costs may be incurred by the labour and time required to sample for natural enemies in addition to pests. This cost will likely vary by crop and the natural enemies scouted. In cotton, for example, the cost of scouting for pests is slightly less than $20/ha (Williams, 2014). Even if this cost doubled with the addition of natural enemy scouting it would still appear to be more than offset by the value of biological control in this crop (Table 4.2).

Within an EIL/ET framework, Brown (1997) suggested that biological control operates by raising the ET because natural enemies are able to suppress pest population growth and either delay or even prevent pest density from exceeding the EIL. The incorporation of natural enemies into ETs acts to reduce risk in decision making, because these decisions are founded on more complete knowledge of pest dynamics and the factors that affect these dynamics (Onstad *et al.*, Chapter 7). Most biological control based thresholds developed to date are grounded on heuristic approaches that may or may not involve explicit models (e.g. Hoffman *et al.*, 1990; Zhang and Swinton, 2012). For example, biological control-informed thresholds were developed for the management of *Bemisia tabaci* in cotton based on understanding the association between the densities of generalist predators and declining pest populations (Vandervoet *et al.*, 2018). With this knowledge, predator–prey ratios were established that indicated suppression of pest populations at or near conventional, pest-only thresholds. If ratios were favourable, this could result in the delayed application or elimination of insecticides and a concomitant reduction in control costs. If ratios were unfavourable, it could lead to earlier application of control tactics. In either instance, grower risk of making the wrong decision was mitigated by either a reduction in unnecessary yield or quality loss or an unnecessary expenditure on insecticides. While pest-centric thresholds alone can facilitate conservation of natural enemies by ensuring that insecticides are applied only when needed, the further integration of natural enemies into the decision process can place explicit value on biological control.

Habitat manipulation

Perhaps the most active area of research in the realm of conservation biological control is engineering of the crop habitat and surrounding landscape to better favour the abundance and activity of natural enemies (Barbosa, 1998; Landis *et al.*, 2000; Gurr *et al.*, 2004; Heimpel and Mills, 2017). Despite the level of attention that has been paid to understanding how habitat manipulation and modification of the landscape can facilitate biological control, there still remain very few studies that have attempted to estimate the economic value of this approach (Table 4.2). Several studies have attempted to quantify the economic value of adding plant diversity to increase biological control, including ground covers (Aguilar-Fenollosa *et al.*, 2011; Colloff *et al.*, 2013), hedgerows and flowering borders (Gurr *et al.*, 2016; Morandin *et al.*, 2016), or examining the role of landscape diversity more generally (Landis *et al*., 2008). Food sprays were shown to enhance the value of biological control in cotton in Africa (Mensah *et al*., 2012) and providing bat shelters near rice (*Oryza*) fields in Spain (Puig-Montserrat *et al*., 2015) or nesting boxes for kestrels near fruit trees in the USA (Shave *et al*., 2018) enabled biological control of caterpillar and fruit-eating bird pests, respectively. Finally, data sourcing and modelling have been used to assign economic value to diversifying natural enemy communities (Letourneau *et al*., 2015; Daniels *et al*., 2017), even while there was no specific habitat manipulation. Based on the limited data available, we did find that conservation biological control via habitat manipulations did have the highest economic value compared with other approaches to conservation (Fig. 4.4), but as noted, the costs of manipulation are not always captured leading to some overestimates of value. In some cases, the cost of manipulations are more costly than alternative control tactics for the same level of pest suppression (Schmidt *et al*., 2007). In other cases, the costs of establishing and maintaining beetle banks in the UK have been estimated, but the benefits they provide in pest control have not been quantified (Thomas *et al*., 1991; Collins *et al*., 2002). Overall, recent syntheses seem to suggest uncertain conclusions on the role of non-crop habitats in enabling improved biological control in nearby crops (Bianchi *et al*., 2006; Karp *et al*., 2018). If growers are going to invest and adopt such approaches to conservation biological control, we need more data on expected benefits and costs. The few examples available show significant value, but these are perhaps case specific and difficult to extrapolate more generally.

Considerations for Moving Forward

Biological control of insect pests is an integral tactic of modern IPM. The number of studies quantifying the economic benefits of biological control remains small relative to the total number of all such programmes. Yet, the estimates from those studies suggest biological control is universally beneficial to growers and society and has immense value. Basic economic concepts and methods guide estimations of economic value on biological control services. Simple partial budgeting, economic surplus modelling, benefit–cost analyses and contingent valuation are among the most useful tools. Studies that attempt to quantify economic outcomes of biological control of arthropod pests with natural enemies may be especially necessary for introductory and conservation biological control because they often require public investments. But, economic analyses have been conducted on fewer than 1% of all introductory biological control projects targeting arthropod pests. The economic value of these few examples is large, with an overall BCR of 61:1, and a total NPV of over \$31 billion, or \$37.35 million per evaluated project (2018 US\$). While relatively few economic analyses have been conducted on the efficacy of augmentation biological control, the industry was valued at \$1.7 billion in 2016 with a 15% growth rate since 2005. Conservation represents the oldest form of biological control practice, and the few studies that have examined economics suggest highly variable value (average of \$74/ha) dependent on the value of the crop being protected and on the approach to conservation.

Connecting economic concepts and methodologies to biological control efforts is needed to support adoption of this critical tactic of IPM. Interaction among diverse scientists and stakeholders will be required to measure the inclusive benefits and costs of biological control. However, focus on gaining greater accuracy in measurement should be balanced with additional effort to educate both end-users and public institutions about the immense value of biological control in order to spur greater adoption, and investment in research and implementation.

Constraints to uptake of biological control

Sixty years after the integrated control concept was suggested as the path forward in the management of arthropod pests, arguably IPM remains only weakly supported by biological control. Why? Other reviews point out many technical, policy, regulatory, communication, cultural, perceptual and other constraints to the implementation of biological controls (Cullen *et al*., 2008; Wyckhuys *et al*., 2013, 2019; Barratt *et al*., 2017; Shields *et al*., 2019). Creative solutions are also on the horizon with many technical solutions to research on identifying the natural enemy definitively, understanding ‘who eats whom’, genetically modifying the biocontrol agent for better efficacy, or the plant for signalling recruitment (Gurr and You, 2016). Global drivers of change impinging on interactions among natural enemies, pests and plants in our agroecosystems will continue to challenge biological control innovations, including agricultural intensification, land-use change and climate change (Crowder and Harwood, 2014). There is a pressing need for larger-scale studies, spatial and temporal, of biological control. Crowder and Harwood (2014, p. 3) conclude that, 'all too often we have limited insight into the effectiveness of natural enemies in production farming systems'. They also conclude that even with trophic linkages known, statistically measured reductions in pest populations are not clearly related to improvements in crop yield. Clear, demonstrated economic benefits will be needed to stimulate uptake of biological control by farmers. And given the few economic evaluations so far conducted, perhaps this is one prominent reason why biological control remains only weakly integrated with chemical control in IPM today.

The work reviewed herein and previously in Naranjo *et al.* (2015) points to net benefits to farmers and society. Even failures in biological control appear to be offset by the extremely high values of the successes realized. Society, however, is demanding greater and greater accountability of private and especially public investments. Economic measurements are needed to spur more innovation and adoption of biological control in IPM. Biological control, too, is innately good; it likely has 'existence value' to growers, the developers of IPM and the public. But, cultures harbour heavy biases that can potentially harm the uptake of biological control by farmers. Entomophobia remains among the top fears of western peoples (Looy *et al.*, 2014; Chapman University, 2018), and there is tremendous downward pressure on biodiversity in fruit and vegetable production fields because of exceptionally low aesthetic thresholds where insects, pest or beneficial, are considered contaminants (sensu the 'produce paradox'; Palumbo and Castle, 2009).

Thus, even with the large economic benefits demonstrated, can biological control become a more integral part of IPM under these many constraints? Naranjo *et al.* (2015) suggest that one way for biological control to achieve parity in consideration with other tactical alternatives is by making more investments in its valuation and broadening the scope of that valuation to capture all benefits to society (e.g. human health and air, water and environmental quality). However, with the huge impact of the value of money and the complications of discounting noted in this chapter, perhaps what is needed are grower-level analyses. The new studies since 2015 continue to point to the tremendous value of biological control, even if these are not all inclusive evaluations.

What is ostensibly lacking are more working examples of grower implementations of biological control integrated with chemical controls. Crowder and Harwood (2014) note that agricultural intensification and other global forces are placing huge demands on per-unit-area production and suggest many strategies for biological control in a 'chemically intensive world'. In addition to discovering and developing working examples of biological control at a field level, researchers of IPM need more estimates of the impact these tactics have on the grower bottom line, some of which could perhaps be driven by simpler CVM approaches that capture their willingness to pay for a non-market benefit or enable them to avoid some risk.

Hard technology, advantage and challenge to biological control

In the context of natural enemies and insecticides, the colloquial terms of 'hard' and 'soft' are used to signify when pesticides are broad spectrum and safe to beneficials, respectively. However, this should not be confused or conflated with hard and soft technologies, which are material entities and human-mediated (typically, knowledge-based resources), respectively, that drive our technological world. The dichotomy is imperfect, however useful nonetheless, especially when considered as a continuum. Even hard technologies can be softened and soft technologies hardened. In terms of IPM, a hard technology is a material entity like a treated seed, an insecticidal-traited variety, or an insecticide. These are hard to make, generally easy to use and complete but subject to breaking (e.g. by resistance). An augmentative approach, like a microbial pesticide or purchased inputs of natural enemies also can be hard technologies. Soft technologies, on the other hand, are knowledge-based and therefore human-mediated. This makes them relatively 'simple' to produce, though the science that sits behind, for example, guidelines for biological control or an IPM strategy is complex. Because humans are needed to activate and use these technologies, they are 'difficult' to use and by definition incomplete. However, soft technologies are extremely flexible and this can be seen in progressive revisions and improvements to strategies and tactical use guidelines (Reisig *et al.*, Chapter 9). Over the past half century, many of our harder technologies (e.g. seeds and pesticides) are being softened by the extensive amount of use instructions and understanding needed to properly deploy them as part of an IPM strategy (Anderson *et al.*, 2019).

Agricultural intensification needed for a food-secure world will continue to depend on chemical pesticides and other hard technologies made available through molecular advances. Because most material products or harder technologies available for pest control are priced by the technology provider, this greatly simplifies a grower's perceived costs and benefits, albeit without capturing external costs, for example, of resistance or environmental degradation, or benefits like reduced pesticide use and subsequent common-pool gains in environmental health. Arguably, private suppliers can more easily profit from these hard technology innovations, leaving the supply of soft technologies, like the knowledge-intensive resources needed to deploy conservation biological control, largely to the public sector. Conversely, for example, an action threshold developed to guide conservation biological control (e.g. Vandervoet *et al.*, 2018) is a soft technology that defies easy monetization and marketing by private interests. But hard technologies will continue to be subject to high regulatory costs and resistance, no matter how innovative, and increasingly subject to patent protections that will maintain higher costs to producers. However, some of these innovations (like seeds and plants as products of genetic engineering) will likely be much more focused in their targeting of pests; for example, by turning on expression only when needed or only in specific plant tissues. As with selective insecticides (Torres and Bueno, 2018), these may be much more supportive of biological controls and other critical ecosystem services like pollination. However, as technologies increasingly 'harden', they will become increasingly subject to breakage (often due to resistance). And, even if they don't, the development of 'soft', knowledge-intensive technologies will need to greatly increase just to keep pace with these innovations, potentially reducing other potential scientific effort on the public good that is biological control – just consider the vast scientific investment in refugia management in transgenic insecticidal crops over the past three decades.

A renaissance for conservation biological control may be upon us, in part due to the advancement of selective tactics in hard technologies. But the challenge is to develop far more working examples of its successful integration with chemical controls and other hard technologies. An additional challenge is to develop all the knowledge-based resources that guide what is tantamount to eco-engineering at a field and farm scale, and which includes outreach that surmounts communication and perceptual barriers to grower adoption. There have been advances in the body of ecological and biological information about natural enemies, but with less emphasis on working systems of biological control for direct grower use and much less on the economic and other perceptual barriers to its adoption. This leads to the conclusion that there is a growing gap between biological control knowledge and its implementation at the farmer level (Wyckhuys *et al.*, 2018a). Efforts to assemble transdisciplinary teams of scientists that address the social and economic demands of the system will likely help spur adoption while helping advance public policy that supports the application of biological control.

Future wars may well be fought over the availability of food. The World Bank projects that a 50% increase in food supply will be needed to feed more than 9.8 billion people expected by 2050 (United Nations, 2017). Even today, the United Nations Food and Agriculture Organization estimates that more than 842 million people are undernourished. At the same time, powerful, new technologies will be developed and compromised by poorly integrated strategies for pest management (e.g. due to resistance, lost biodiversity or compromised ecosystem services). No matter the challenge, few things would support the durability, resilience and sustainability of IPM and the future of our food supply more than the full integration of the biological control tactic with chemical control (and other hard technologies) as originally proposed 60 years ago by Stern *et al.* (1959). Whether that tactic comes in the form of introduction, augmentation or conservation, IPM is stabilized by the favourable ecological balance that is created by biological control. When properly understood and implemented, biological control can reduce both primary and secondary pest pressures, respond numerically and functionally to all pest densities, including target pest changes potentially associated with climate change, and has comparatively rare risks for resistance (Holt and Hochberg, 1997; Onstad, 2014). Given its track record for positive economic outcomes, even the most basic economic valuations of biological control should help farmers understand, use and actively manage this tactic in sustainable IPM systems of the future.

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