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Economic Value of Biological Control in Integrated Pest Management of Managed Plant Systems

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Abstract

Biological control is an underlying pillar of integrated pest management, yet little focus has been placed on assigning economic value to this key ecosystem service. Setting biological control on a firm economic foundation would help to broaden its utility and adoption for sustainable crop protection. Here we discuss approaches and methods available for valuation of biological control of arthropod pests by arthropod natural enemies and summarize economic evaluations in classical, augmentative, and conservation biological control. Emphasis is placed on valuation of conservation biological control, which has received little attention. We identify some of the challenges of and opportunities for applying economics to biological control to advance integrated pest management. Interaction among diverse scientists and stakeholders will be required to measure the direct and indirect costs and benefits of biological control that will allow farmers and others to internalize the benefits that incentivize and accelerate adoption for private and public good.

INTRODUCTION

Ecosystem services: the services provided by nature that humans benefit from and depend upon

The grand challenge to meet the increasing demands for food and fiber by a rapidly growing global population requires innovative solutions. A key component to meeting these demands will be protecting crops from pest losses while conserving limited natural resources and maintaining environmental quality through ecologically and economically sound integrated pest management (IPM) practices. Biological control (BC) is a key ecosystem service and an underlying pillar of IPM (71, 117).

The importance of natural enemies for pest control has been appreciated for over a thousand years (112), but only relatively recently have scientists and practitioners attempted to assign economic value to BC (29). The complexity of evaluations attempted varies with cropping systems as well as with the approach used. Classical BC attempts to manage primarily invasive pests through the introduction of exotic natural enemies. Spectacular and long-term results have been achieved in some instances, and the few studies examining economic outcomes have suggested favorable returns on investment (29, 50, 58, 81). Augmentative BC relies on a one-time or repeated supplemental introductions of natural enemies to suppress pests. Results from limited economic analyses have been mixed (16, 131). Conservation BC involves effecting positive changes to the environment or in control tactics to favor the abundance and activity of natural enemies. Here, specific economic evaluations have been extremely rare even though ecosystem-level estimates show significant value (21, 77). BC as a whole potentially provides one of the highest returns on investment available through IPM, even though its economic value is rarely estimated. In general, the lack of rigorous economic assessment is pervasive in IPM systems (97).

Pest management is only one component of agricultural production, but one that has important economic consequences associated with control options, including control costs, production outcomes, and environmental and societal effects. Understanding the economic value of the key ecosystem services supplied by BC will help to broaden its utility in crop protection and raise its stock among all stakeholders of agriculture, including those who make funding decisions that spur needed innovations. Several informative reviews have addressed the general topic of BC economics (10, 25, 50, 56, 66, 102, 121, 139). Our focus here is to review and assess the economics of arthropod BC by arthropod natural enemies in managed plant systems. We start by examining the analytical approaches useful for valuing BC. Next, we briefly review and update the record of progress in economic evaluation of classical and augmentative BC. We then focus on the economics of conservation BC, which has received the least attention and is more dispersed in the literature, and for which methodology and concepts are still developing (25). We close with a call to arms that highlights the constraints, challenges, and opportunities for assessing the economics of BC to advance IPM.

METHODS AND ANALYTICAL APPROACHES

Methods of estimating economic values of BC vary by the scale and scope of the analysis and by the fundamental questions they seek to address. We consider the objectives of three types of analyses. The first objective is to consider individual growers' farm-level costs and benefits of adopting BC. Here, critical questions are whether growers have an economic incentive to adopt BC and how that might alter insecticide use. The second objective is to consider effects of BC adoption by growers as a group over a broader geographic region. Here, key issues are the economies of scale of BC adoption and how private incentives may diverge from collective incentives. An example would be the management of mobile pests through an area-wide approach. This type of analysis may also consider cross-commodity effects across different grower groups. The third and most comprehensive objective is to consider the effects of BC on society as a whole. Pest management decisions by growers can provide benefits or impose costs on other members of society that are not reflected in the private costs growers incur or the private benefits they gain. When such costs and benefits are external to grower incentives and decisions, pest management decisions may not achieve socially desirable outcomes (e.g., too little protection for workers or lack of biodiversity protection). This raises policy questions of how to induce grower decisions to account for broader costs and benefits (25). Options might include regulation of pesticide use, incentive payments to growers for environmentally beneficial practices, and/or public investment in research and extension to develop and promote BC. Benefit-cost analysis, which considers both grower private costs and benefits and external costs and benefits, can be used to evaluate regulatory policies and the net benefits of public investments in BC.

Averting costs: a method of estimating costs of risks based on the costs people incur to avoid those risks

Ex ante economic evaluation/analysis: an economic assessment/analysis that attempts to predict future economic benefits

Ex post economic evaluation/analysis: an economic assessment/analysis that focuses on realized economic benefits

Externalities: costs or benefits that accrue to others besides the agents directly involved in an economic transaction

Approaches to Measuring Farm-Level Benefits of Biological Control

One approach to measuring farm-level benefits of BC is to compare farm profits with and without BC. Although farm profits are an admittedly narrow measure of the benefits of BC, they are critical. Agricultural practices that are not profitable are unlikely to be adopted. A major difference in profits will be avoided costs (pest damage plus tactical costs like insecticides) (39, 43, 57, 90, 99, 101, 105, 123). The basic approach is to assume profit-maximizing behavior by farmers and measure differences in yields, crop quality (affecting price), and pest control costs. This can be done via ex ante studies, which consider the potential impacts of yet-to-be-implemented BC practices against current practices (57, 78, 96, 107). Ex post analyses are retrospective, evaluating an implemented BC program against a counterfactual scenario of not adopting the program, or comparing performance between adopters and nonadopters (6, 18, 42, 84, 109, 129, 135).

Simulation models can play an important role in extended field assessment. Models can be static, collapsing decisions and results into a single period (e.g., 116), or dynamic (e.g., 148), following a series of decisions throughout the growing season. Dynamic models can be potentially better at capturing the nuances associated with multiple pest problems, such as secondary pest outbreaks that can occur because of failure to account for the effects of insecticide applications on natural enemies (54). Ecoinformatics approaches (108) may also play an important role by allowing simple models to capture the decision-making actions of growers over a broad area.

Externalities

Pest management decisions can generate externalities: costs or benefits that accrue to others besides those directly involved in an economic transaction. Examples of externalities in pest control include long-term effects on worker health, effects on water quality, and ecological effects. A common approach in environmental economics is to measure the difference in outcomes (such as insecticide use or farm profits) when externalities are accounted for and when they are not (36). An implication of externalities is that if growers cannot capture the external benefits of BC, they may underadopt those practices. Another way to view this is that growers need to internalize the external costs of alternative pest control approaches such as insecticide use. For example, use of a science-based risk estimation tool such as ipmPRiME can be used in farmer education and policy analyses as well as adapted to estimate environmental and human health costs of pesticide use (65). Overall, externalities lead to divergence between private profitability and collective economic welfare.

Growers can impose positive or negative externalities on each other. In such cases, it is important to assess the effects of BC adoption on growers as a group. For example, growers spraying for pests in one crop could reduce regional populations of natural enemies important for controlling

BENEFIT-COST ANALYSIS

Benefit-cost analysis is a formal approach to quantifying the benefits and costs of public or private projects, programs, or regulations that follows four steps: Define the project's geographic scope and time horizon, characterize and enumerate project inputs and outputs, estimate benefits and costs of these inputs and outputs, and compare benefits and costs over a time interval of interest. Both private and external benefits and costs are considered. Private benefits and costs measure effects on those directly involved in market transactions and can be readily measured in monetary terms. External benefits and costs include effects such as species preservation, environmental pollution, and worker health risks, which may not enter the calculus of private decision makers. Economists use various nonmarket valuation techniques to quantify such impacts in monetary terms. Discounting is used to convert benefits and costs accruing at different points in time to a common, current monetary value. 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. Evaluation metrics include net present value (discounted benefits minus discounted costs) and the benefit-cost ratio (discounted benefits divided by discounted costs).

pests in another crop (48). Another example is the effect that growers collectively adopting BC might delay the evolution of insecticide resistance. By limiting or delaying pesticide applications and contributing to pest suppression, BC can postpone the onset and cost of pest resistance (75). It should be possible to measure the benefits of BC in terms of the extended years of efficacy of certain insecticides, especially given the costs of insecticide development (114). It would also be possible to estimate effects of BC on pollinators and the associated benefits on overall crop production. Again, the emerging field of ecoinformatics (108) could represent an approach that allows such regional information to be cataloged and applied in such analyses.

Benefit-Cost Analysis

Benefit-cost analysis is an analytical framework that can be applied to all levels of the economic objectives outlined above and is frequently used to evaluate public policies of all kinds (see sidebar, Benefit-Cost Analysis). Within BC, benefit-cost analysis has typically been applied to evaluating classical BC where programs occur over wide geographic and temporal scales (58). Costs generally include the labor and materials costs associated with exploration, importation, quarantine, release and distribution, verification of establishment, and sometimes evaluation of efficacy. 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. Successful classical programs can generate long-term benefits, sometimes relegating a pest to noneconomic status. Thus, the flows of costs and benefits need to be compared over time (50, 58).

Benefits can be compared in terms of net benefits (benefits minus costs) or, more typically, through benefit-cost ratios. These ratios have generally been >1 for successful classical BC programs that have been assessed (58). The temporal perspective of classical programs requires discounting to compare costs and benefits occurring at different points in time. Discounting converts future costs and benefits into current value equivalents (present value). The real discount rate allows for inflation, which affects the relative value of current and future money. There is no consensus about any single discount rate to apply (36). Higher rates are usually used to compare programs in terms of the opportunity cost of foregoing alternative private investments. Lower rates

Present value: the value of money in the future based on its current value

Discount rate: percentage rate at which the value of future money is reduced (discounted) to arrive at its current value equivalent

Opportunity cost: the value of a benefit that would have occurred if an alternative action had been taken are generally associated with government projects providing benefits to future generations. Extant analyses have used variable rates and accrued benefits and costs over variable periods of time (50, 58; see section Classical Biological Control, below). Sensitivity analyses have been used in some cases to examine effects of variable discount rates, time horizons, and other factors (33, 80, 87).

Several issues influence the interpretation of benefit-cost analysis in evaluating BC. First, whereas data to estimate avoided costs can be obtained from farm accounting data or economics statistics, estimating benefits and costs of pest control decisions requires consideration of potential environmental and societal effects that are not directly measured by market prices. These externalities must be measured using nonmarket valuation techniques (36). In rare cases, social costs are considered, such as declines in social welfare associated with pest impacts (140) and the environmental impacts of alternatives (e.g., 13, 115). In measuring program costs and estimating benefits, evaluators must make decisions about the starting point and what to include. The broader the definition of inputs contributing to the program, the greater program cost estimates will be. Many times, the inclusion of nonmarket factors will increase benefit estimates. Finally, benefits of BC practices, regardless of approach, will be volatile because annual crop values are volatile owing to changes in yield, acreage, and prices. Evaluation of programs over multiple years or using longer-term averages can provide estimates less sensitive to yearly variation in prices (e.g., 26, 87, 92).

Contingent valuation: a technique for estimating value based on what people are willing to pay for a particular service

Contingent Valuation

The contingent valuation method (CVM) is a direct, survey-based approach to elicit people's willingness to pay for some benefit or avoid some risk. Questionnaires in CVM studies identify some environmental resource or product with environmental or health attributes and posit a change in the resource or attributes (11, 36, 41, 68). A series of questions is designed to accurately elicit respondents' willingness to pay to effect or avoid the change. CVM is frequently used because it has the potential to measure nonuse values, benefits people enjoy that do not involve depleting a resource. An example is the value a person might attach to the existence of a species and the loss they would feel from its extinction (11, 36).

Studies have applied CVM to estimate consumer willingness to pay for reduced exposure to pesticides (38) and for crops or urban plants protected by BC and other IPM tactics in particular (41, 68). Even if consumers are willing to pay premiums for using BC, growers may not capture such premiums without some form of an inspection and labeling system to provide verification to consumers. CVM studies have also been used to estimate farmer willingness to accept reduced profits due to limiting pesticide use in order to obtain environmental benefits, including protection of beneficial insects (41, 76). CVM has been the subject of substantial criticism, however, with questions raised about its ability to generate reliable and consistent measures of willingness to pay. The hypothetical nature of CVM questions does not require respondents to make actual economic choices, which can lead to biased and unreliable responses. Also, CVM approaches generally sample willingness to pay at a single point in time and are weaker in measuring dynamics changes through time that may be influenced by and subject to education. Although widely used to measure environmental benefits, CVM remains controversial (36, 51, 55).

CLASSICAL BIOLOGICAL CONTROL

Classical BC was formally initiated in the late nineteenth century with the introduction of *Rodolia cardinalis* and *Cryptochaetum iceryae* against the cottony cushion scale (*Icerya purchasi*), an invasive pest of citrus in California. Since then the BIOCAT database has shown that over 5,000 natural enemy introductions in nearly 200 countries have been made for over 400 introduced arthropod pest species (45, 58). However, despite the number of programs attempted relatively few quantitative assessments have examined net economic benefits.

DeBach (29) summarized some of the first ex post assessments and estimated a net benefit of $110 million resulting from successful outcomes of one weed and four insect BC projects in California over the period 1923–1959. Subsequent ex post compilations provide economic outcomes for 32 arthropod pest species involved in 59 attempts in 39 countries (50, 58, 63), including a large coordinated project for control of cassava mealybug (*Phenacoccus manihoti*) in 27 African nations (92). Benefit:cost ratios ranged from 1:1 to 12,698:1, but these figures involved a variable number of years (10–40 years) during which benefits were assumed to accrue and discount rates varied (4–10%).

New evaluations, older ones not covered in previous compilations, and reevaluations based on new data involve a variety of fruits and vegetables (1, 6, 33, 80, 87, 96, 129, 134, 140), pasture/forage systems (82, 141, 146), floriculture (26), and urban systems (67, 68). All these evaluations indicate benefit:cost ratios >1 (5:1 to >1,000:1) or positive net present values, but again over variable time horizons and discount rates. High returns on investment are frequently associated with programs with wide geographic impacts because the initial cost of the program may be small relative to the regional scale of benefits (50). Although the BIOCAT database is neither all-inclusive nor current, proportionally this effort has resulted in about a 25% success rate in establishing exotic agents and with about 2.5–3.8% of all introductions resulting in complete or substantial control on a global basis. Despite these high failure rates, arguably the benefits accruing from successful programs more than cover the expenses of failed programs (58). By comparison, 140,000 insecticidal compounds need to be screened to find one successful compound (0.0007%; 114). Once that insecticidal compound has been identified, it can take upwards of $250 million and from 8 to 12 years to develop and register a new material (114) with an ultimate benefit:cost ratio of 2–5:1 (3). The development of insecticide resistance is an additional cost, a cost that is likely to be much lower in BC (62). Most estimated benefits of classical BC are conservative, as they do not include externalities such as nontarget and off-site effects of the insecticides or other practices replaced. Most economic evaluations also have examined benefits over a restricted time frame even though results are generally long-term. Furthermore, assessments do not include the benefits of introducing the agents into multiple countries after the initial program development costs in a single country. All this suggests that more comprehensive valuations would show that classical BC has even greater net benefits than existing studies have demonstrated.

The costs of classical programs are typically born by the public sector, whereas the beneficiaries are growers and society at large (58). However, there are examples of private investment. An ex ante contingent valuation estimated that homeowners would be willing to pay 21 times more for BC than for conventional insecticides to control eucalyptus snout beetles (*Gonipterus scutellatus*) attacking urban trees in California (68). A program for control of Argentine stem weevil (*Listronotus bonariensis*) in pasture grasses in New Zealand was based on a system where the agents were reared commercially and then sold to growers. By 1998 >600,000 parasitoids had been bought and released at 112 sites (82).

Both the BIOCAT (45) and ROBO (Release of Biological Organisms, **http://www.ars-grin.gov/nigrp/robosrch.html**; 22) databases have strengths and weaknesses, but neither track economic valuations as called for in a new, more inclusive database (138). A new, open access version of BIOCAT is under development and may eventually provide benefit-cost information (15).

AUGMENTATIVE BIOLOGICAL CONTROL

Augmentative BC is largely a market-driven enterprise with a defined, but constantly changing, economic value. It is estimated that approximately 230 natural enemies are available from over

500 suppliers with an end-user market value >$200 million globally (131). This does not include several large-scale, government-funded operations in China, Mexico, and several South American countries (132, 136). Despite global growth in the industry, natural enemy production appears to be declining in the United States (137). Relative to expenditures for insecticides, the research and development investment in augmentative BC development is an order of magnitude lower (131).

Although augmentation has a market value, it remains critically important to assess its practical operational value. Augmentation is commonly valued relative to the insecticides replaced, in terms of both benefits and costs. A relatively recent review focused on augmentative BC by examining studies that met strict experimental standards (16). Roughly one-third of the studies examined included economic evaluations. With several exceptions (e.g., 85, 123), most studies suggested that natural enemy releases resulted in lower returns compared with insecticide alternatives owing to higher costs of control, differential efficacy, or both.

Several additional ex post analyses of field studies have shown that integrating augmentation with insecticides or biopesticides can result in positive net gains in sweet corn, tomato, cotton, soybean, and mango production (43, 46, 74, 101, 122). Based on a thorough accounting of costs and benefits, including the research investment, an ex ante analysis showed that integrated mite (*Tetranychus* spp.) control involving release of pesticide-resistant predator mites (*Metaseiulus occidentalis*) in almonds could yield 14:1 to 34:1 benefit:cost ratios and 280–370% annual rates of return (57). Economic benefits estimated from other ex ante analyses have been mixed (78, 107).

The largest market sector for augmentative BC is the greenhouse industry, primarily in Europe and the United States (131). Here, too, the economic benefits have been mixed, with the costs of augmentative control far exceeding the comparative costs of insecticides (59, 60, 118, 133) except under certain high-value conditions, like organic production, that preclude use of some of the most effective synthetic pesticides (42). Other studies have estimated the cost dynamics associated with augmentation with a goal of implementing a BC-only solution (106). In general, it is argued that the vitality of the natural-enemy-producer industry in Europe and the widespread use of augmentative BC, particularly in European greenhouses, suggest that it is an economically viable approach to pest control, with a 2–5:1 benefit:cost ratio, similar to the benefit:cost ratio for insecticides (3, 103, 131). The vitality of the augmentative BC industry in certain parts of the world indicated that more comprehensive economic analyses of this type of BC should be possible.

CONSERVATION BIOLOGICAL CONTROL

Conservation BC involves changes to the crop environment, including the landscape in which the crop is embedded, to favor the abundance and pest-suppression activity of native or introduced natural enemies. This involves minimizing factors that can harm natural enemies and/or providing them additional food and shelter (4, 73, 130). Arthropod natural enemies inhabit multiple cropping systems, but their value goes largely unnoticed until disruptions—for example, by the application of broad-spectrum insecticides—precipitate target pest resurgence or outbreak of secondary pests (117). The fact that little attention has been paid to understanding and estimating the economic scope of conservation BC (25) is perhaps related to the failure to recognize its critical importance to IPM.

The economics of conservation BC is somewhat unique. As with classical BC, natural enemies present in the environment provide an ecosystem service that may benefit growers who are not directly paying the costs. However, the end user may invest, either monetarily or via the decision-making process, to conserve native or introduced natural enemies and realize direct benefits. In augmentation BC, the monetary investment is the purchase and supplemental deployment of natural enemies. In conservation BC, the monetary investments are indirect: for example, costs associated with different choices of insecticides and/or methods for their deployment [e.g., economic thresholds (ET)] (23, 117), the provisioning of flowering borders (49), and the planning and planting of farm landscapes (47, 119). Industry also has ostensibly invested in conservation BC through development of a broader range of more selective insecticides, selective genetically modified (GM) traits for multiple pest species, and sometimes structured insecticide resistance management programs to preserve the efficacy of these selective products.

Economic threshold (ET): the level of pest density or injury at which control action should be taken to avoid reaching the EIL

Broad Estimates of Ecosystem Services

"Ecosystem services" has become part of the vernacular in many fields of study related to agriculture, natural resources, and the environment (27, 144), and there is considerable interest in valuation methodology (125). In a seminal paper (21), BC (defined as trophic regulation of populations) was valued at $572/ha globally (2013 constant dollars) across multiple biomes. Cropland estimates were drawn from Pimentel et al. (104) and suggested a value of $33/ha (2013 dollars). Others estimated a value of $5.5 billion (2013 dollars) just for insect natural enemies attacking native pests of crops in the United States, but this estimate may be very conservative (72). Large-scale, ecosystem-level estimates like these have opened the conversation, but field-specific estimates will matter most to decision makers considering adoption or implementation of conservation BC.

Insecticides and Natural Enemy Conservation

Insecticides are one of the more important and widely used tactics in IPM, but they can also become barriers to effective BC. More than 50 years ago, Stern et al. (117) suggested that through rational planning and implementation, insecticides and natural enemies could be integrated in an additive manner to manage pests. Although there are still few explicitly validated examples of this type of integration (39, 88), the potential is great, especially given the broad array of selective insecticides and selective GM crops now available. Even with superior chemical tools and despite an expansion of the definition of IPM through time, integration of tactics today has not been uniformly well developed and adopted in all systems (e.g., 30, 145). Stern and colleagues (117) managed to elegantly integrate the use of a comparatively broad-spectrum organophosphate with conservation BC in the spotted alfalfa aphid (*Therioaphis maculata*)–alfalfa system. After 50 years of integrated control and IPM development, the scientific community should be in a better position to measure the value of IPM through dedicated efforts to measure the true value of conservation BC, especially where insecticides are also used.

Some IPM programs have been assessed economically (91, 95, 97). Typically the focus is on estimating the avoided cost of insecticides where BC might be one of several integrated tactics (e.g., 12, 40, 57, 115). Studies providing sufficient data to estimate a value for arthropod natural enemies alone are rare (**Table 1**) and without exception are examples of an avoided-cost approach. The avoided cost of insecticides from an array of cropping systems ranged from $0/ha to $2,202/ha. Studies compared two economic-threshold-based IPM systems for whitefly (*Bemisia tabaci*) in cotton that resulted in equal crop yields: one based on broad-spectrum insecticides and one using selective insect growth regulators that conserved primarily generalist predators (88, 90). Life table studies showed that differences in pest dynamics and control were associated with conserved natural enemies and other natural control factors (89). The $92/ha estimated net benefit of conservation BC does not account for the increase in potential secondary pest outbreaks, increased insecticide resistance in pests, or greater environmental risks typical of the conventional insecticide system. This program is part of an overall strategy that has saved Arizona cotton growers >$400 million in control costs and yield loss since 1996 (88), with conservation BC being a large contributor to these financial gains. A comparative study in Nicaragua showed that farmers who did nothing to control

Table 1 Estimated value of conservation biological control in various systems

Crop system	Pest species	Country	Natural enemy	CBC value ($US/ha)[a]	Prod. costs ($US/ha)[b]	Notes	Reference(s)
Insecticide comparisons							
Gossypium hirsutum (cotton)	*Bemisia tabaci*, *Lygus hesperus*	United States	Generalist predators, parasitoids	92[c]	3,077	Experimental, selective versus broad-spectrum insecticides; includes other natural control factors	89, 90
Brassicae oleracea (cabbage)	*Plutella xylostella*	Nicaragua	Parasitoid, predatory wasps	2,202[d]	4,272[e]	Farm-scale grower practice (calendar sprays), additional unmeasured gains in resistance management noted	7
Hordeum vulgare (barley)	*Rhopalosiphum padi*	Sweden	Ground-dwelling predators	65 (organic) 46 (conventional)	515	Experimental and modeling studies	99
Triticum spp. (wheat), *Hordeum vulgare*, *Trifolium* spp. (clover), Gramineae (grass), *Salix* spp. (willow), *Alnus rubra* (alder), *Corylus* spp. (hazel)	*Rhopalosiphum padi*, *Sitobion avenae*, *Metopolophium dirhodum*, *Delia coarctata*	Denmark	Ground-dwelling predators	15 pasture 14 biomass 0 cereal	NA NA 515	Experimental, farm trials	105
Triticum spp., *Daucus carota* (carrot)	*Acyrthosiphon pisum*, *Psila rosae*	New Zealand	Ground-dwelling predators	50[f] (organic) 0 (conventional)	4,418[e] (organic) 3,566 (conventional)	Experimental, farm trials	109
Biological control–based economic thresholds							
Solanum lycopersicum (tomato)	*Helicoverpa armigera*	New Zealand	Parasitoids	16[g]	8,566	Farm-level experiment	135
Glycine max (soybean)	*Aphis glycines*	Canada	Generalist predators	26[h]	594	Experimental, farm trials	52
Glycine max	*Aphis glycines*	United States	Generalist predators	5–38	428	Data sourcing, modeling	148
Experimental manipulation/models							
Gossypium hirsutum	*Pseudatomoscelis seriatus*	United States	Generalist predators	27	1,038	Validated insect/plant model	116
Theobroma cacao (cacao)	*Conopomorpha cramerella*, *Helopeltis sulawesi*	Indonesia	Ants	917	2,321[e]	Experimental exclusion	142

(*Continued*)

Table 1 ***(Continued)***

Crop system	Pest species	Country	Natural enemy	CBC value ($US/ha)[a]	Prod. costs ($US/ha)[b]	Notes	Reference(s)
Gossypium hirsutum	*Helicoverpa armigera*, *Diparopsis watersi*, *Earias huegeli*, *Pectinophora scutigera*, *Nezara viridula*, *Dysdercus sidae*	Benin	Generalist predators, parasitoids	276[i] (organic)	490	Farm trials with beneficial food sprays	84
Habitat manipulations, landscape structure							
Citrus sinensis (orange citrus)	*Pezothrips kellyanus*	Australia	Predatory mites	2,286–7,396[j]	4,158	Farm-level experiment	18
Glycine max	*Aphis glycines*	United States	Generalist predators	37	428	Farm-level trials, experimental exclusion	72
Nonarthropod examples							
Gossypium hirsutum	*Helicoverpa zea*	United States	Free-tailed bats	235[k]	1,774	Data sourcing, modeling; includes social costs of insecticide	13
Gossypium hirsutum	*Helicoverpa zea*	United States	Free-tailed bats	58–271 (Bt cotton) 109–960 (non-Bt)	1,774	Data sourcing, modeling	35
Coffea arabica (coffee)	*Hypothenemus hampei*	Jamaica	Insectivorous birds	344	2,861[e]	Experimental exclusion	69
Theobroma cacao	*Helopeltis sulawesi*, *Conopomorpha cramerella*, Lepidoptera, Coleoptera, Aphididae, Orthoptera, Blattodea	Indonesia	Insectivorous birds and bats	730	2,366[e]	Experimental exclusion	79

Abbreviations: Bt, *Bacillus thuringiensis*; CBC, conservation biological control; NA, not available; Prod, production.
[a]All figures in 2013 constant US$ (gross domestic product: implicit price deflator, **http://research.stlouisfed.org/fred2/series/GDPDEF/**).
[b]Various sources: USDA Economic Research Service, **http://www.ers.usda.gov/data-products/commodity-costs-and-returns.aspx#.UysYX17t5OR;** Cotton Incorporated, **http://www.cottoninc.com/fiber/AgriculturalDisciplines/AgriculturalEconomics/Cotton-Production-Budgets;** Ontario Ministry of Agriculture, Food and Rural Affairs, **http://www.omafra.gov.on.ca/english/crops/field/soybeans.html;** Nicolas Gergely (World Bank), **http://www.worldbank.org/afr/wps/WPS125_Benin_Cotton_Study.pdf;** European Commission—EU FADN, **http://ec.europa.eu/agriculture/rica/pdf/cereal_report_2012.pdf**.
[c]Difference between cost of selective and conventional sprays.
[d]Difference between net return of grower practice and doing nothing.
[e]Mean crop value per hectare instead of production costs.
[f]Average over both pests and all farm sites.
[g]Difference between cost of conventional and biocontrol-based threshold outcome.
[h]Based on cost of one avoided pyrethroid spray.
[i]Difference between net return of food spray and untreated control.
[j]Does not account for the cost of ground cover establishment and maintenance.
[k]Moderate infestation converted to value per hectare.

diamondback moths (*Plutella xylostella*) in cabbage but managed the crop similarly to growers who sprayed a variety of insecticides saved $2,202/ha (7). Parasitoids and predatory wasps were more abundant in unsprayed fields, but pesticide resistance was a factor and sprays were not applied based on thresholds; so, the avoided costs of BC are likely greatly inflated. Studies comparing organic and conventional production for cereals, pastures, and biomass crops show more moderate benefits from conservation BC (99, 105). A multicrop study in New Zealand estimated no benefit from conservation BC in cereals (109). Although outside the intended scope of this review, the economic value of bats (*Tadarida brasiliensis*) in BC of cotton pests (e.g., *Helicoverpa zea*) in Texas has been estimated through avoided cost of conventional (13) and biotechnology-based management systems (35; **Table 1**).

Economic injury level (EIL): level of pest density or injury at which the cost of control equals the value of economic damage prevented

Economic Thresholds and Biological Control

The ET is a fundamental component of most IPM programs and provides for a rational, economically based framework for control decisions (100, 117). The inclusion of BC in this decision process and the associated concepts and theory are relatively recent developments (9). Only a handful of ETs incorporating BC have been developed (19, 20, 37, 44, 52, 53, 61, 86, 111, 135, 147), with few deployed operationally (19, 52, 61, 135) and still fewer that have placed a value on the integrated conservation BC (52, 135, 148, **Table 1**).

The operational ET is derived from the more explicit economic injury level (EIL) (100, 117). Brown (9) formalized this relationship and provided a framework for modeling BC into the ET. The model discounts the rate of pest population growth depending on the level of BC. The result is an elevated ET and a smaller margin between the EIL and ET. Although few ETs including BC started with a formal EIL, most of them raise the ET based on natural enemy abundance or function. One system in New Zealand allows the ET to increase or decrease depending on natural enemy abundance (135) because the original ET was developed within a background of extant BC, a common situation in many systems where natural control forces already exist (98).

The end result of using BC information to refine the ET is generally either delayed or eliminated sprays, and thus avoided costs. Indirect savings also result from reductions in uncertainty, thus reducing risks of making the wrong decision (9). Overall, these avoided costs should, at a minimum, exceed the cost of collecting the natural enemy data (9). As an example, scouting costs in US cotton average $21/ha (143). The addition of natural enemy scouting would likely lead to a minor cost increase that would be considerably less than the value of conservation in cotton (**Table 1**). This assumption would need to be examined in each crop system.

Brown (9) argued for the integration of BC into the ET rather than the EIL because the latter was already a well-established concept, both operationally and mathematically. Nevertheless, the EIL ($= C/VIDK$) consists of parameters directly influenced by BC. Cost of control (C) and proportion of damage prevented by the control action (K) could, for example, differ when a selective control method is used, especially one with delayed action, like application of an insect growth regulator or release of an augmentative agent. Crop value (V) might also differ if there were a market demand that favored more biologically based management. Even the injury-damage (ID) relationship could be altered by the nature of the control agent and its effect on pest growth and damage potential (e.g., parasitoid or slower-acting selective insecticide). Perhaps these factors deserve additional attention as EIL/ET theory and concepts develop.

Experimental Manipulations and Models

Other approaches have been used to estimate conservation BC value within an avoided-cost framework, but without consideration of insecticides (**Table 1**). The avoided cost of damage to yield was estimated with a detailed insect-crop model to arrive at a value of $27/ha for a suite of generalist arthropod predators attacking cotton fleahoppers (*Pseudatomoscelis seriatus*) in cotton (116). Supplemental food sprays to attract and retain arthropod natural enemies were deployed to avoid a net value of $276/ha in yield loss from multiple insect pests (*Helicoverpa armigera*, *Diparopsis watersi*, *Earias huegeli*, *Pectinophora scutigera*, *Nezara viridula*, *Dysdercus sidae*) of organic cotton in Benin (84). The exclusion of ants (142) and insectivorous birds and bats (79) on Indonesian cacao, and exclusion of insectivorous birds in Jamaican coffee plantations (69), showed avoided costs of yield loss of $344–900/ha (all monetary values are in US dollars throughout).

Beetle bank: area of diverse flora bordering a crop field and providing habitat for beneficial insects and other animals of conservation concern

Habitat Modification/Landscape Management

Management and manipulation of agroecosystems has long been a focus in conservation BC (130), and investigations have expanded considerably in recent decades (4, 49, 70, 73, 124). Still, valuations of habitat management are extremely rare (**Table 1**). The relationship between pest regulation and the composition and diversity of landscapes surrounding crop fields showed that arthropod natural enemies were more abundant 74% of the time and pests less abundant 45% of the time in more diverse landscapes (5). However, few studies have measured crop damage and none have estimated crop yields that would permit at least rudimentary estimates of the economic value of biodiversity in pest management. In an Australian citrus system, orchards with ground covers harbored much larger populations of predatory mites (Mesostigmata) and smaller populations of damaging thrips (*Pezothrips kellyanus*). The control value ranged from $2,000/ha to >$7,000/ha (18), though the costs of ground cover establishment or maintenance were not included. Using predator exclusion, Landis et al. (72) estimated BC of soybean aphids (*Aphis glycines*) to be worth $37/ha in four US midwestern states, and the overall value of this ecosystem service was found to decline with increasing corn production and a corresponding reduction in crop diversity in the region (72).

Several studies have estimated the cost of habitat manipulation but have not quantified the benefits associated with these changes. Beetle banks have been studied in the United Kingdom for their utility in enhancing local biodiversity for pest suppression in neighboring crops and in serving other conservation needs. Costs for their establishment and maintenance have been estimated; however, only hypothetical estimates of their value in pest control are available (17, 120). The costs of providing flowering resources for natural enemies in crop fields, including competitive effects on the crop plants, have been estimated; yet, the value of potential enhancement of yields due to the resulting natural enemy conservation has not been measured (8, 24). Whereas a few studies have examined the effects of adding diversity on crop productivity (e.g., 14), the costs of habitat manipulation or gains from pest control overall have not been quantified. Ground covers may enhance natural enemy abundance but are sometimes more costly than alternative control measures (110). Overall, more holistic studies that account for all the relevant components are needed. This will help to demonstrate ecologically whether habitat management is effective for enhancing natural enemies and suppressing pests while also showing that these manipulations are realistic and provide a net benefit to the grower and beyond (5).

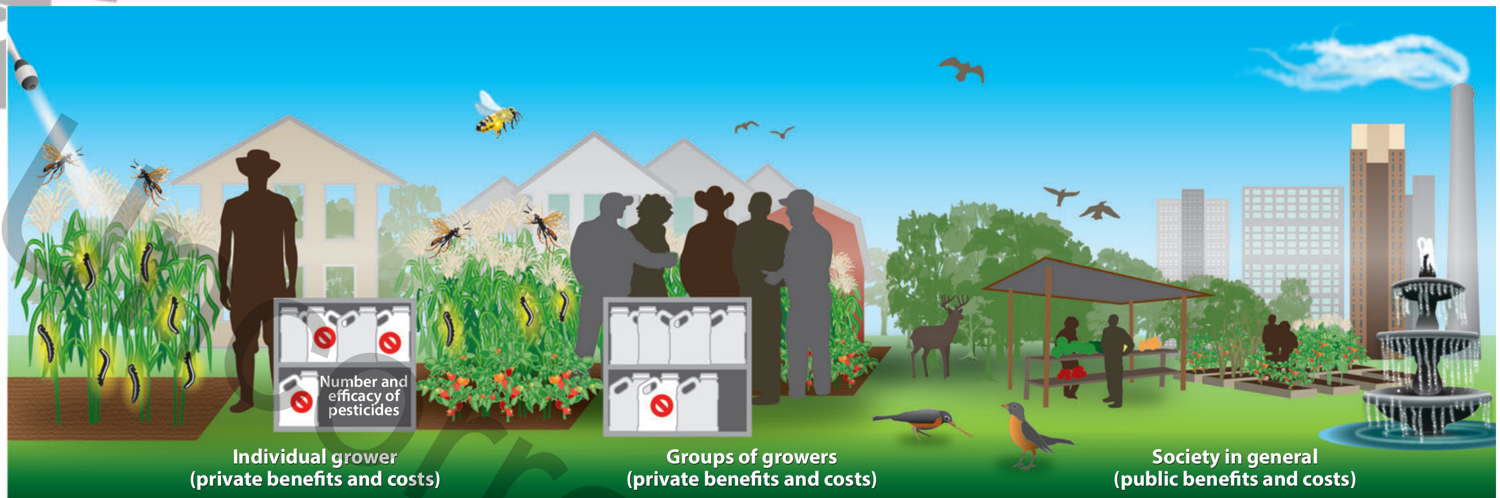
Synthesis

Through the lens of avoided costs, the value of BC, regardless of approaches, is tied directly to the value of alternative pest control methods and/or the production value of the commodity. This is reflected in the few examples for conservation BC (**Table 1**) where the generally greater value of horticultural crop production was matched by greater values of conservation BC. Contrasts between conventional and organic systems where pest control costs may be lower and crop values higher provide further examples. Just like the fundamental EIL, production values and control costs are dynamic in time and space; thus, as these costs and values change, so does the value of conservation BC. Notwithstanding these facts, the economic entomology community has often proposed at least static ETs and/or EILs as starting points for management. However, the BC community has invested little in even initial static valuations of conservation BC or other forms of BC generally. Further generalizations are difficult until we have a much greater body of conservation BC valuations in hand. Overall, the valuation of all types of BC needs to be placed in a broader context that accounts for grower and societal benefits and costs.

More broadly, entomologists, economists, and others should pursue together more holistic and comprehensive benefit-cost analyses that augment avoided-cost approaches with more sophisticated and creative measurement systems. We offer, as a starting point, a perceptual transect that outlines likely factors requiring consideration and probable methods for their measurement in the development of BC benefit-cost assessments (**Figure 1**). The factors considered and methods to measure their value vary by the scale and scope in which we view them. For all factors for which there are markets determining pricing, direct measures through avoided costs and other procedures are valuable and convenient (e.g., crop yield, quality, or pest control costs) (e.g., 7, 18, 72, 84, 99). Other concerns such as insecticide resistance and regulatory issues may be addressed through modeling approaches, whereas quality-of-life matters will likely require nonmarket approaches such as CVM (38, 41, 68, 76). Individual growers prioritize their attention on overall farm profitability. Groups of growers are affected by additional factors including regional pest suppression and efficacy/durability of chemical control agents, BC agents and pollinator services, and regional environmental quality, which can all be influenced, negatively or positively, by the action of a single or just a few growers. For these elements less-direct methods such as modeling on a regional scale, data-mining exercises, or nonmarket valuation techniques may be needed to derive meaningful market values (54, 108, 148). Finally, a broad range of factors important and relevant to society as a whole can be potentially addressed by all three assessment approaches in comprehensive analyses that most closely approach the true benefits and costs of BC (**Figure 1**).

A CALL TO ARMS

The precursor to IPM was the integrated control concept, which called for pest control through a complementary combination of chemical and biological control (88, 117). Farmers and researchers are very aware of the direct costs of chemical control options. Yet, more than 50 years later, we struggle to identify the value of BC, especially conservation BC, which is a central tenet of IPM. IPM today is largely identified as a risk management approach to pest control (127) that should protect economic, environmental, and human health interests from pests and pest management tactics. IPM should be rooted deeply in an economic foundation properly assessing the values of multiple control tactics, including conservation BC. Though some have directly challenged the concept or its implementation (e.g., 30, 145), IPM is a durable and robust concept. Yet, there remains a dearth of literature and information on system-specific economic value of BC that would inform decision making (25, 97). Part of the problem can be traced to difficulties in determination of EILs and their associated ETs for even much simpler systems based on a single tactic (e.g., chemical control). Fewer than 1% of research papers in economic entomology reported economic evaluations of pest management tactics (97). Yet, there are new approaches suggested in economic entomology such as using ecoinformatics, which might help bypass some of the more difficult experimental issues in IPM (108).



	Individual grower (private benefits and costs)	Groups of growers (private benefits and costs)	Society in general (public benefits and costs)
Market-based assessments	• Crop yield and quality • Primary, secondary, and resurgent pest control • Scouting and habitat management • Crop prices received • Farm profits • Changes in BC or other tactical efficacies • Access to domestic/export markets • Pesticide regulations and related licensing, training, and record keeping	• Crop yield and quality • Primary, secondary, and resurgent pest control • Scouting and habitat management (regional) • Crop prices received • Farm profits • Changes in BC or other tactical efficacies • Access to domestic/export markets	• Food price premiums or discounts • Regional employment effects • Changes in natural lands and community garden productivity • Drinking water quality • Soil, water, air, and other environmental remediation • Public costs in pesticide regulations and related licensing, training, and safety education
Dynamic models, simulations, and data mining (e.g., ecoinformatics)	• Pest resistance • Change in costs of pesticide regulations • Crop quality • Secondary pest control • Ecotoxicological effects/risks • Household pesticide exposure and water quality	• Pest resistance • Change in costs of pesticide regulations • Regional effects on grower collective costs and profits • Regional changes in pest suppression, BC, pollination, and other ecosystem services	• Employment effects • Change in costs of pesticide regulations • Net present value or rate of return to public investments in BC • Water, air, and other environmental pollution effects on morbidity/mortality
Nonmarket valuation (e.g., averting cost, hedonic pricing, or travel-cost analysis; contingent valuation)	• Crop prices and discounts received • Grower willingness to pay for improved household water quality • Grower willingness to pay for reduced household pesticide exposure	• Regional groundwater and other environmental quality	• Wage premiums for risk • Consumer willingness to pay for foods with positive environmental attributes • Willingness to pay to avoid water, soil, or air pollution; for species protection; or to avoid residues in foods and environment • Farmworker health impacts • Willingness to pay for public spaces that are impacted by pesticides or BC/pollination services • Value of wildlife viewing/hunting

For conservation BC to be considered on an equal footing with other tactical alternatives, more research and investment in its valuation are needed from the scientific community. Such advances could represent a potential step-change increase in the development of sustainable IPM systems, which arguably are static and often overdependent on singular tactical approaches like chemical control, contrary to Stern and colleagues' vision (30, 117, 145).

Transdisciplinarity: real-world, complex problems solved through stakeholder-engaged, integrative research and learning that exceeds, blurs, and exploits boundaries of and space between disciplines

Research on valuation of conservation BC is limited, and the factors governing this are manifold. Disciplinary silos are often cited as factors preventing the true transdisciplinarity (31, 97) that is likely required for valuation of conservation BC. Pest management experts, social scientists (e.g., evaluations specialists), and economists should establish relationships early in the joint research and/or deployment development process to insure that the experimental approach is comprehensive and inclusive of all needed factors and measurements (2, 25, 56, 83, 126). Many times, ex post approaches are constrained by incomplete data collection or inadequate design. With a problem-solving orientation, pest management specialists may tend to focus on the development of conservation BC technology and approaches (i.e., the solutions) to pressing pest control needs rather than systematic evaluation criteria. As noted, classical BC is largely an investment of the public sector, whereas augmentative approaches are mostly an investment of the private sector. Conservation BC lies between, and this fact probably is reflected in lower investments, in general, let alone effort dedicated to valuation.

Although the above factors may operate and limit progress in this important area, they were not major issues identified by a group of cotton entomologists or agricultural economists in a recent survey (**Supplemental Appendix**; follow the **Supplemental Materials link** from the Annual Reviews home page at **http://www.annualreviews.org**). When asked, "What do you see as the barriers or challenges to measuring (in dollars) the economic value of conservation BC in your cotton system [for cotton entomologists; agricultural economists were asked about agricultural systems]? (Please list all factors you can identify.)," these scientists ($N = 76$; 37% response rate) responded with approximately 100 ideas centering around challenges in valuing components of the system, experimental design and analysis, resources, and contexts and disincentives to this type of work.

Many scientists cited difficulty in estimating benefits and costs associated with conservation BC (35% of factors identified by surveyed scientists) (**Table 2**; **Supplemental Table 1**). Valuation of system components is daunting because of the temporal and spatial scales over which benefits can accrue (47); and because benefits are often not priced in the market, and nonmarket valuation methods are unavailable (**Figure 1**). In addition, probability distributions of pest manager outcomes are poorly known or completely unknown. Given the close association between chemical and biological control (117), many times benefits of conservation BC are completely confounded with more general gains of the specific IPM system (32, 88–90). As a result, producers may be unable to discern, and scientists measure, specific benefits attributable to conservation BC. In addition, there are disincentives to maximizing grower outcomes when the advising pest management professionals derive a private benefit from sales of chemical or biological crop inputs to the producer.

Market or nonmarket valuation methods are constrained by the many and complex interactions between pest and beneficial species in the system, and these are central to the compromises and difficulties in experimental design and analyses of resulting data (26% of factors identified;

Figure 1

Perceptual transect depicting scale and scope of benefit-cost analyses needed to properly estimate values of biological control. Abbreviation: BC, biological control.

Table 2 Identification of challenges or barriers to valuation of conservation biological control (percentage of responses)[a]

Population	N	Total responses given	Valuations: identifying and/or estimating costs of inputs or outputs (%)	Experimental design/analysis (%)	Resources (%)	Contexts and disincentives: impact on interest in conservation BC adoption and research (%)
US agricultural economists	8	30	53	30	0	17
Cotton entomologists	20	70	27	24	4	44
Total surveyed	28	100	35	26	3	36

[a]Cotton entomologists were surveyed with respect to their cotton system; agricultural economists were asked about agricultural systems in general. See **Supplemental Appendix** for survey content and more details (follow the **Supplemental Materials link** from the Annual Reviews home page at **http://www.annualreviews.org**.

Table 2; **Supplemental Table 1**). Damage avoided, tactic substitution, and other approaches to empirical testing of conservation BC efficacy and value are frustrated by the same temporal and spatial constraints that affect benefits valuations in general. In this case, experiments are rarely large enough, sufficiently randomized, replicated, or properly contrasted to positive or negative controls to avoid serious limits on conservation BC valuation inference. For example, the impact of "moving" treatments where the positive benefits of conservation BC spread and affect nearby non–conservation BC treatments limits progress by entomologists in testing (64).

Even though there are rather significant challenges for entomologists in implementing effective experimental designs, those surveyed rarely cited insufficient resources in general as major impediments to this type of work (3% of factors identified; **Table 2**; **Supplemental Table 1**). However, resource issues could be related to the broader set of overriding concerns and contexts that result in lack of grower interest in conservation BC, which in turn acts as a major disincentive to scientific effort and progress in this area (36% of factors identified; **Table 2**; **Supplemental Table 1**) (25). Cotton entomologists in particular cited problems with heavy insecticide use (including frequency and intensity as well as the lack of selective insecticides) and with grower reluctance to depend on natural enemies as impeding any progress in conservation BC, let alone measurement of its value. Interestingly, low insecticide use was also cited as an impediment to progress in this area, presumably because growers and researchers do not perceive enough need for pest control, let alone valuation systems development for conservation BC.

Despite the dearth of literature on valuation of conservation BC and considerable difficulty in research in this area (25, **Table 1**), the public perceives economic value of goods and services all the time, and in sometimes very complex ways. Similarly, in pest control systems pest managers must perceive values even if the research to support a specific value is lacking. As part of the US Department of Agriculture's (USDA) Agricultural Resource Management Survey (128), growers were asked, "Was protection of beneficial organisms a factor in your pest control decisions for this field?" Adoption rates (percentage of acres) were generally low for many crops, but cotton growers responded most favorably (48.9% in 2000 and 25.5% in 2007). A 2014 survey was designed to ascertain how people perceive the value of conservation BC in their cotton system (**Supplemental Appendix**). Pest managers (licensed pest control advisors) in Arizona valued conservation BC in their cotton system at \$108 ± \$123 (standard deviation)/ha (N = 19; 73% response rate; range, \$0–494/ha). At the same time, cotton research and extension entomologists from the United States and Australia estimated the value of conservation BC in their cotton system at \$49 ± \$51/ha (N = 18; 40% response rate; range, \$0–185/ha).

Although they were arrived at through a gestalt process, these values are in line with experimentally derived estimates of the value of conservation BC (especially for Arizona cotton; 89, 90; **Table 1**). It may be that education about conservation BC and then detailed surveys of stakeholder-perceived value, a rigorous contingent valuation approach, is a more tractable and fruitful approach to identifying and communicating the value of this ecosystem service (e.g., 41). However, some scientists in this survey (**Supplemental Appendix**) cited a shortage of qualified personnel for engaging, communicating, educating, and training growers as well as for deployment of conservation BC systems (**Table 2**; **Supplemental Table 1**). Indeed, a major constraint on deployment is the uncertainty in speed and scope of efficacy possible that therefore makes conservation BC a knowledge-intensive enterprise (139). The value of a CVM approach could be strengthened through repeated use over time with an integrated and comprehensive user educational campaign. Onstad & Knolhoff (97) also point to the serious lack of economics training among economic entomologists. Whereas lack of skill leads to naive and incorrect approaches in economic entomology, many capable people in the field are operating with incomplete information and serious time constraints. These facts lead researchers to a default of using avoided costs as their singular approach to valuation (e.g., **Table 1**), which can appear as a lack of skill or training but may really be a reflection of the funding available to collect the data required.

Although progress in valuation of conservation BC has been slow in the past, the environment is changing rapidly to focus scientific effort on assessment sciences as a basis for targeting research and outreach and for purposes of accountability in use of public funds. IPM assessment is now widely considered requisite to any successful proposal, and evaluation plans are almost always demanded by US federal funding agency requests for proposals (97). For instance, the USDA National Institute of Food and Agriculture's Regional IPM Centers have dedicated evaluation specialist staff (93, 94, 113), working groups (34, 83), and funded projects in the areas of IPM program evaluation and IPM assessment. In addition, resources are being made available to nonevaluation specialists through these investments, including an online tool kit for assessing IPM outcomes and impacts (83), which has received more than 3,000 page visits from 300 unique users in 26 countries in its first two months. As funding sources continue to emphasize the need for preplanned project evaluation, there will be increased incentive for researchers to work directly with social and economic scientists and achieve transdisciplinarity. We expect that as part of this larger change in scientific culture, new efforts and new valuations of conservation BC will emerge, hopefully with transdisciplinary and not merely interdisciplinary linkages established at project conception.

Perhaps beginning with the seminal work and definition of ecosystems services by Daily and contributors (27) and continuing today with global issues and concerns for biodiversity and pollinator health, there is greater interest and scrutiny about the value of key ecosystem services, including conservation BC. This scientific energy needs to be directed at meaningful valuations of conservation BC that will further incentivize scientists, policy makers, funding agencies, and farmers/pest managers alike to invest more heavily in this key component of IPM. It is, however, this last audience that remains key (25, 47). Without sufficient demonstration of farmer-level benefits, even if largely indirect, conservation BC cannot develop to the levels needed to advance IPM to where it will need to be in a sustainable world (**Figure 1**). Advances with valuation of conservation BC, with all its inherent complications and difficulties, will likely open up new understanding and opportunities to evaluate other key elements of IPM, such as resistance management, which have also defied easy valuation. Daily et al. (28) challenged the scientific community to develop the knowledge and tools needed to predict and quantify the value of ecosystem services and concluded, "Price is by no means the only thing that affects peoples' decisions. However, if we can get the price closer to being 'right,' everyday behavior and decisions will be channeled toward a [sustainable] future . . . ." Similarly, regarding the use of conservation BC in IPM decision making, it's time to deliver!

SUMMARY POINTS

1. Biological control (BC), a key ecosystem service and underlying pillar of IPM, likely provides one of the highest returns on investment available in IPM, yet its economic value is rarely estimated. Valuing BC will broaden its utility in crop protection and raise its stock with all stakeholders of agriculture, including those who make funding decisions that spur needed innovations.
2. Many benefits of BC are environmental and associated with reductions in insecticides. These are more difficult to estimate than on-farm benefits such as improved yields or lower pest control costs, requiring nonmarket valuation. Despite ongoing debates over contingent valuation, it remains a widely used technique for environmental valuation. It can be used to evaluate consumer willingness to pay for foods grown using approaches that reduce insecticide use or perceived risks and to examine grower preferences for BC methods.
3. Classical BC is largely a publicly funded endeavor with social and private benefits, whereas augmentation is a market-driven enterprise that benefits those investing. Naturally occurring BC has social benefits that go largely unnoticed and unvalued, and investments to enhance conservation BC are often indirect, with benefits that are more difficult to quantify.
4. Habitat management, both locally and regionally, has been an active area of investigation for enhancing conservation BC; however, economic issues have been largely ignored. More inclusive study is needed to demonstrate not only that habitat management is effective for enhancing natural enemies and suppressing pests, but also that these manipulations are realistic and profitable for the grower and merit both public and private investment.
5. Education about conservation BC and then detailed surveys of stakeholder-perceived value may be a tractable and fruitful approach to identifying and communicating the economic value of this ecosystem service.
6. Entomologists and agricultural economists perceive significant challenges and barriers to valuation of conservation BC: (*a*) difficulties in identifying and estimating all the costs of inputs and outputs, (*b*) intractable problems of experimental design and need for new approaches to analysis, and (*c*) significant contexts and disincentives to the adoption of conservation BC by end users that become overriding barriers for entry into this field of research.
7. With notable exceptions, progress in valuation of BC, and conservation BC in particular, has been poor. Transdisciplinarity should become the goal of scientists involved with BC, where the complex real-world problem of managing pests through natural processes orients our efforts to a solution that directly engages the actors affected and develops new insights between, across, and beyond the disciplines supporting valuation of this key ecosystem service. Only through early interaction among diverse scientists and stakeholders may we better identify and evaluate the direct and indirect costs and benefits

of BC, such that farmers and others can internalize the benefits that incentivize and accelerate adoption of BC for private and public good.

8. Entomologists, economists, and others should collaboratively pursue more holistic benefit-cost analyses that go beyond avoided-cost approaches and use more sophisticated measurement systems. A perceptual transect is offered that outlines likely factors requiring consideration and probable methods for their measurement in the development of comprehensive BC benefit-cost assessments that range from individual growers to society as a whole (**Figure 1**).

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