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REVIEW

Using economics to inform and evaluate biological control programs: opportunities, challenges, and recommendations for future research

Katherine Lee · Shana McDermott · Linda Fernandez

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Abstract Assessing the economics of biological controls in pest and invasive species control is pivotal for guiding research and decision making. The field of economics provides numerous systematic methods to assess the impacts and values created by biocontrol programs, as well as weigh the trade-offs of allocating resources to research, development, and management activities. This article discusses economic methods used to evaluate the impacts and quantify the net benefits of biological control programs, including data needs and shortcomings of methodologies. We cite examples from the literature on the economics of biological control to provide insight into the various ways in which economics contributes to the design, evaluation, and development of recommendations for biological control programs. We then discuss general trends and highlight knowledge gaps, providing suggestions for enhancing the use of economics in the analysis of biological control programs in the existing literature. This article is intended to serve as resource for researchers and policymakers interested in assessing benefits and trade-offs of biological control programs through the lens of economics.

Keywords Biological control agents · Pest management · Economic analysis · Ecosystem services · Cost–benefit analysis

Introduction

Biological control (or biocontrol) programs offer a target-specific approach to managing pest (target species) populations. By leveraging natural ecological interactions, these programs deploy natural enemies to suppress and control target species populations. Often used in integrated pest management programs, biocontrol agents are especially useful in situations where eradication is not feasible or when the scale of the infestation is too extensive (Naranjo et al. 2015). While biocontrol programs can have varying objectives from pest eradication to conservation of native species, one key advantage is their potential to become self-sustaining (Bale et al. 2008). This can lead to economic and conservation benefits not offered by chemical or manual pest management methods (Bale et al. 2008). However, biocontrol programs can also have substantial up-front costs

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K. Lee (✉)
Agricultural Economics & Rural Sociology, University of Idaho, Moscow, ID 83844-2334, USA
e-mail: katherinelee@uidaho.edu

S. McDermott
Department of Economics, Trinity University, San Antonio, TX, USA

L. Fernandez
Department of Economics and Center for Environmental Studies, Virginia Commonwealth University, Richmond, VA, USA

including development, regulatory approval, and land manager coordination. Often, rewards are realized years after program initiation (Ehler 1998) creating challenges for measuring and evaluating success.

For over a century, biocontrol agents have been used to manage target species. The efficacy and potential advantages of biocontrol are well-recognized but evaluation of the economic implications, especially by economists in economic disciplinary journals, is surprisingly scarce. The majority of evaluations of biocontrol programs are published in non-economics journals. It is intriguing that many of these articles providing insight into measuring and weighing the costs and benefits of programs are likely not reviewed by economists. This is important because economic methods such as cost–benefit analysis, return on investment analysis, and cost-effectiveness analysis are just a narrow subset of economic methods that could be applied to evaluation of biocontrols. The involvement of economists in biocontrol evaluation can improve the scope of analysis, as well as thoroughness and accuracy of results.

While the number of articles evaluating biocontrol programs within the field of economics remains relatively small, economic theory and modeling have been extensively used in related fields of invasive species management and conservation or management of natural resources (Eiswerth et al. 2018). The parallels between these other fields and biocontrol imply there is significant potential for incorporating economics into biocontrol research.

To begin conversations with economists about applying economic methods to biocontrol, it is essential to understand what economic analyses typically entail in terms of modeling and required inputs. Most generally, economic analyses evaluate how to efficiently allocate or use scarce resources. Through statistical and numerical methods these analyses guide the evaluation of policies and decisions to best allocate limited assets like money or time. Central to economic analyses is the understanding of trade-offs or opportunity costs—the potential outcomes foregone when resources are directed in a specific manner. For example, if financial resources, labor, and capital are invested in one management strategy, the opportunity cost is that those resources become unavailable for different activities. Opportunity costs could be measured in terms of economic outcomes, including industry revenues, social net benefits, non-market values, or conservation outcomes such as a metric of biodiversity, populations, or ecosystem processes.

Some realities of biocontrol programs make them hard to evaluate using the more straightforward modeling frameworks. Non-monetary costs and benefits, delays between timing of costs and realization of benefits, and uncertainty in long-term program success create challenges to planning and evaluating biocontrol programs. The lack of detailed documentation regarding release specifics—such as the precise locations, quantities, and timing of agent releases—poses notable challenges for empirically evaluating the success and impact of biocontrol initiatives (Marten and Moore 2011; van Driesche and Heinz 2016). Moreover, the scarcity of spatial and temporal data that track populations, geography, and ecological impacts of biocontrol agents further complicates assessment (Nordblom et al. 2002; Maluleke et al. 2021). Specific economic methods have been designed to address such knowledge gaps and data challenges. We see opportunities for their employment.

The objective of this article is to provide an overview of economic methods that are suitable for evaluating different aspects of biocontrol programs. We focus the discussion on how economic analyses can be conducted in the absence of data or other informational shortcomings. When possible, we present examples from the disciplinary economics journals. Our goal is to introduce readers who might be less familiar with these outlets to new resources for learning about applied economic research in biocontrol and related fields. We specifically highlight methods not yet employed in the field of biocontrol, the niche yet crucial economic literature that evaluates the non-monetary effects of biocontrol agents and methods assessing optimal resource allocation in management. In the next section we highlight general knowledge trends, identify existing gaps, and discuss various challenges, basing our insights on referenced articles and our own observations. Finally, we provide actionable recommendations for practitioners, championing the integration of economic insights into biocontrol program analyses.

Economic evaluation of biocontrol programs

Defining economic impacts of target species and biocontrol agents

Target species can have significant impacts on ecosystem functions, which can in turn affect the ecosystem services that benefit humans (Pyšek et al. 2020). For example, invasive plant species can reduce biodiversity (ecologically problematic), and in turn negatively impact crop pollination, natural pest control, and nutrient cycling (Eiswerth et al. 2018). Invasive species can also lead to changes in water flow and quality, affecting water supply and recreation opportunities (Limburg et al. 2010; Zavaleta 2013; Badiou and Goldsborough 2015; Weber et al. 2021). Some target species just directly impact food production by damaging crops. The objective of biocontrol programs is to mitigate any of these direct or indirect impacts by reducing the populations of target species so that ecosystem functions are recovered (Roy et al. 2023). Measuring the impacts of biocontrol programs requires assessing how the biocontrol agent has changed production of an ecosystem function or service and translating that change into a value or measure of human well-being. First and foremost, measuring the change in ecosystem function or service production is often necessary before estimating its value.

Once the affected ecosystem service has been identified and measured, the next step is to attach a value to that ecosystem service. Some changes in ecosystem service production resulting from target species can be directly valued through changes in supply of natural resources consumed by humans (Roy et al. 2023). In agricultural systems, pest species can reduce crop yields and quality. Similarly, target species can damage forests or urban trees, leading to reduced timber production and the loss of wood-based products or benefits of urban trees, such as home cooling. Target species can also directly affect water quantity and quality by reducing water supply or contaminating water bodies (Campbell and Schlarbaum 2014). These direct effects often can be linked to changes in production of goods and services with well-defined market prices. Determining the value of pest control requires combining the change in ecosystem service production with its per-unit value.

Target species can also have indirect impacts on human well-being through interactions and processes within ecosystems, such as water and nutrient cycling or photosynthesis, that contribute to human well-being through a complex pathway which is difficult to place a monetary value on. For instance, target species can disrupt pollination services by outcompeting or consuming native pollinators, or by reducing the abundance and diversity of flowering plants (Roy et al. 2023). The resulting reduction in pollination services can have ecological impacts beyond fuel, food, or fiber production. There are methods within the field of economics to place monetary values on these indirect values. However, in cases where target species have indirect effects on human welfare, species' impacts to ecosystem services need to be well-defined and quantified to conduct economic valuation or other assessments, which is not a small task.

Some instances of biocontrol program may require monetizing the impact of the biocontrol agent. Market values have impacts tied to the production of goods and services that are exchanged in markets (Varian 1984). In such cases, data from market transactions can be used to value the impacts and changes in ecosystem service production. Non-market valuation methods, on the other hand, are required when the impacts to well-being cannot be mapped to goods and services typically bought and sold in markets. This applies to ecosystem services such as water purification, carbon sequestration, and biodiversity. Non-market valuation methods are also used to measure the intrinsic value that individuals place on the environment or nature, independent of market value or exchange (Boardman et al. 2018). Table 1 provides a summary of the discussion of economic methods discussed below with a corresponding published example of the method applied to biocontrol or invasive species management.

Valuing impacts of target species and biocontrol programs

Estimating the value of impacts of biocontrol to single industry or stakeholder group

The availability of data, including volumes of production and consumption, prices, and expenditures are important for estimating the monetary value of pests that primarily affect goods traded in markets

Table 1 Summary of items from biocontrol programs that could be analysed and recommended economic methods. A selection of in-text references is provided as examples for further reading

Biocontrol item to evaluate	Economic method	Considerations and drawbacks	Example
Bioeconomic modeling for optimal use of biocontrol agent	Economic optimization framework - could be static, dynamic, spatiotemporal, stochastic	Mathematical models—require knowledge of parameters, biological-economic relationships	Epanchin-Niell and Hastings (2010)
Efficient design of biocontrol program surveillance/monitoring	Return on investment analysis, cost-effective analysis, or economic optimization framework	Requires knowledge of relevant species and economic parameters, biological-economic relationships	Springborn et al. (2016)
Planning biocontrol program with uncertainty in program success	Stochastic dynamic model	Mathematical models- require knowledge of parameters, biological-economic relationships	Marten and Moore (2011)
Compare the costs and benefits of management alternatives to relevant stakeholder groups	Benefit-cost analysis	Costs and benefits need to be measured in same units. Non-monetary benefits (e.g., benefits from ecosystem services) translated to monetary	Fraser et al. (2016)
Quantify change in value of ecosystem service production using available market data (e.g., crop yields/prices, housing prices)	Hedonic valuation non-market valuation methods	Price and other datasets must be large enough to conduct statistical analysis	Isely et al. (2017)
Evaluate the change in value of ecosystem service production in absence of value data for specific program	Benefits transfer method	Issues of data quality, transferability, scope, external factors, leading to inaccuracies in estimating value in a new context	Wainger et al. (2018)
Evaluate change in value of ecosystem service production in absence of market data, estimate willingness to pay for pest management	Stated preference non-market valuation methods	Survey method, requires solid survey design, risk of hypothetical bias	Mullen et al. (1997)
Assess stakeholder preferences for pest management alternatives (e.g., chemical, biological), estimate willingness to pay forpest management	Contingent choice non-market valuation methods	Survey method, requires solid survey design, risk of hypothetical bias	Chakir et al. (2016), Jetter and Paine (2004)
Quantify economic impacts to production sectors (e.g, industry, agriculture,	Input-output model	Knowledge of economic theory and socio-economic data requirements	Seawright et al. (2009)
Quantify economic impacts to production sectors (e.g, industry, agriculture, infrastructure) and consumers	Computable general equilibrium smodel	Knowledge of economic theory, computational methods, and socio-economic data requirements	McDermott et al. (2013)
Did benefits generated from program cover costs?	Return on investment analysis, retrospective benefit-cost analysis	Requires ability to translate benefits into monetary values, need complete information on historic and future program costs	Weber et al. (2021), Wainger et al. (2018)
Compare costs of achieving an outcome using different forms of action	Cost-effectiveness analysis	Costs and benefits need to be measured in same units. Non-monetary benefits (e.g., benefits from ecosystem services) translated to monetary values	Maluleke et al. (2021)

including fuel, food, fiber, and sometimes water. Market data can be sourced from industry, government, and individual producers or consumers, to determine the impact of target species and biocontrol. These data include information on prices of goods or services, production costs, traditional pest control expenditures, production levels, imports and exports, or other values relevant to the specific industry or economic sector. Such data may be used to quantify the effects on a single sector or consumer group, or to parameterize larger-scale economic models that estimate the impact on the broader economy.

Much of the existing literature on biocontrol evaluation uses market data (e.g., crop yields and prices, pesticide or other management costs) to estimate costs and benefits. The case studies presented in Cock et al. (2015) provide examples of the diversity of data sources that could be used to value impacts of biocontrol agents. Some examples use government reports to evaluate losses in crop production and exports, while others use survey data from producers paired with reported market prices to estimate impacts. In another assessment, Fraser et al. (2016) quantified the benefits of controlling water hyacinth (*Eichhornia crassipes*) by estimating low, medium, and high volumes of water savings from controlling the aquatic weed, multiplied by an assumed added value of water for agricultural production.

Some existing works define value as the money not spent on other pest management practices. For example, Headley and Hoy (1987) and McConnachie et al. (2003) evaluated cost savings of using biocontrol agents compared to chemical or mechanical control. Maluleke et al. (2021) evaluated the cost savings from reduced use of herbicide on invasive aquatic plants in South Africa. In other evaluations of aquatic weed management, the assumed value of biocontrol is a change in water availability for irrigated crop production. It is important to note that these agricultural production cost savings may omit unknown long-term effects of control, such as herbicide resistance or effects of chemically based pest management.

In a different context, some evaluations measure solely benefits to human health. Richter et al. (2013) defined the benefits of biocontrol through reductions in medical costs. They simulated the change in human allergy incidence resulting from the spread of ragweed in Europe under various climate scenarios. They estimated the number of cases of hay fever and medical costs with different levels of ragweed invasion. Similarly, Mouttet et al. (2018) estimated the reduction in medical costs from ragweed due to biocontrol by an unintentional introduction of the North American leaf beetle (*Ophraella communa*) in the Rhône-Alpes region of France. As another example, Schaffner et al. (2020) determine the healthcare cost savings from introduction of the leaf beetle across Europe. It is important to note that these evaluations solely value health and do not consider the trade-offs of conventional management practices *versus* biocontrol.

When government or market data is not readily available, socio-economic survey and interview methods can inform biocontrol program value by collecting information from stakeholders affected by the pest. Mhina et al. (2016) conducted a survey of 30 cattle producers to determine the extent of forage losses due to invasive mole cricket species in the USA. In another assessment, Dahlsten et al. (1998) interviewed eucalyptus growers to determine the costs of managing insect pests in eucalyptus production in California, USA. De Groote et al. (2003) conducted surveys in villages in Benin to determine whether stakeholders perceived a reduction in the economic burden of water hyacinth to fishing, crop production, and transportation, measuring impact and value of biocontrol. While surveys and data collection from individuals can reveal heterogeneity in experienced economic impacts, data collection can be costly and requires careful construction and piloting to ensure that responses are unbiased (Cameron Mitchell and Carson 2013).

An alternative method to assign value is the benefits transfer approach. Benefits transfer is a method for estimating economic value by applying data from previous studies that have estimated the values in a similar context. For example, data from previous studies estimating the economic benefits of reduced pesticide use can be assumed to apply in a novel context. Benefits transfer is useful when direct measurement of benefits to the study system is not possible due to time, resource, or ethical constraints. In their analysis of water hyacinth control, Wainger et al. (2018) estimate the impacts of reduced water loss on recreational values using benefit transfer, citing existing studies that quantified the value of recreation and applying those values to their study system. It is important to recognize that benefits transfer requires defining and locating values for specific impacts and the assumption that other factors are similar between the original application and the novel one.

Estimating the impacts of biocontrol agents at regional or national scale with economic theory

Many existing assessments of the value of biocontrol agents adopt what Letourneau et al. (2015) and McDermott et al. (2013) define as a "fixed-price changed-value" approach to quantify the market values of biocontrol impacts. A fixed-price changed-value approach assumes there are no spillover effects to other markets, i.e., all other prices remain fixed. McDermott et al. (2013) show that if an analysis is conducted using fixed-price changed-value, results can be flawed. Market prices vary with quantities produced and demanded and the amount of variability (elasticity of supply and demand) depends on the good or service in question. The fixed-price changed-value approach could result in either over- or underestimation of the value of the biocontrol depending on the specifics of the impacts.

Computable general equilibrium (CGE) and input–output models are both used to simulate supply and demand interdependencies between sectors in national or regional economies, addressing the fixed-price changed-value shortcoming. The objective of CGE models is to determine the long-term impacts of exogenous "shocks" to the economy, changes that occur outside of the modeled economic system, such as introduction of an invasive species, that have economic impacts. CGE models are useful in predicting consumer and producer decisions by assessing the "ripple" effects of a price changes on other industries and consumption (see Hosoe et al. (2010) for CGE modeling specifics). These analyses typically present the economic impacts in the form of changes to social welfare, the well-being of consumers and producers, in monetary terms. While we could not locate assessments of biocontrol using CGE models, there is a large literature evaluating the economics of invasive species from which similar assessments of biocontrol impacts could also be conducted. For examples of CGE models assessing the impacts of invasive species, see Warziniack et al. (2011), McDermott et al. (2013), or Apriesnig et al. (2022).

Input–output models track monetary exchanges in the process of transforming raw materials and intermediate products into final goods and services, assessing how exogenous shocks impact production sectors. Input–output models also address the fixed-price changed-value criticism because changes in production levels affect prices in the model. For example, Seawright et al. (2009) estimates of the regional economic impacts of reducing giant reed (*Arundo donax* L.) infestations in Texas, USA and Mexico stemming from changes in irrigation water availability, which affects acres of irrigated crops, crop yields, and prices. Input–output models and CGEs can incorporate impacts to multiple sectors simultaneously, as in Bangsund et al.'s (1999) evaluation of the benefits of controlling leafy spurge (*Euphorbia esula* L.) that considers the benefits of control to agricultural systems and recreational benefits.

Non-market valuation methods used in analysis of biocontrol

In the examples given above, all the values were linked to resources exchanged in markets, with identifiable prices. Non-market valuation methods are needed to estimate the economic impacts when the affected outcome lacks a market price. These methods can also assess individual values for non-market goods like recreation, landscape aesthetics, and cultural significance. The two major types of non-market valuation are stated preference and revealed preference approaches. Hanley and Barbier (2009), Champ et al. (2017), and Hanley and Roberts (2019) provide detailed texts on methodologies, benefits, and pitfalls of non-market valuation approaches. Despite debates about the appropriateness of placing monetary values on non-market costs and benefits, we need consistent units of measure for comparing benefits and program costs.

Stated preference methods utilize surveys or similar instruments to elicit peoples' preferences and willingness to pay for different levels of environmental quality over a wide range of non-market values. Respondents are presented with scenarios, projects, or policies that will improve environmental quality and asked if they would be willing to pay a sum of money to experience that improvement. For example, Jetter and Paine (2004) used stated preferences to determine household rank and value for biocontrol, chemical treatment, and bacterial spray treatment of a tree pest in California, USA. They found that consumers had the highest willingness to pay for biocontrol (US$ 485 annually per household) and the lowest willingness to pay for chemical treatments (US$ 23 annually per household). Fleischer et al. (2013) used focus groups to conduct a stated preference valuation *ex ante* to estimate willingness to pay to conserve pollinators in Israel. Stated preferences can also be used to evaluate the effects of a biocontrol program *ex post*. Chakir et al. (2016) used a stated preference method to determine whether the Asian ladybird (*Harmonia axyridis*), which preys on aphids but has become invasive in France, had a net positive or negative impact on social welfare. An important caveat of stated preference methods is the need for hypothetical scenarios in which respondents are asked whether they would pay, but they are never actually required to follow through on payment. The hypothetical nature of stated preferences requires careful survey design, specification of statistical analysis, and results should be interpreted and used with caution.

Revealed preference methods on the other hand, use observed behavior to determine preferences for non-market amenities and monetary values for environmental quality. Hedonic pricing is a type of revealed preference method that examines how environmental quality affects market prices, such as property values. Liao et al. (2016) estimated the impact of Eurasian watermilfoil (*Myriophyllum spicatum* L.) on housing values in Northern Idaho, USA, finding the presence of the water-fouling plant decreased property values by up to 13%. While their assessment did not include valuation of a biocontrol program, this serves as an example for how hedonic valuation can be used to quantify the monetary value of controlling pest populations. Hedonic valuation is data intensive and require sound statistical analyses. It is important to note that the value estimated in hedonic valuation just measures the value of attributes that are directly observable (e.g., water clarity) and tied to the value of a tangible asset (a house or property), therefore does not estimate values of ecosystem services not directly related to home value such as biodiversity.

Frameworks for assessment of biocontrol programs

Creating effective biocontrol programs demands efficient use of money, people, and natural resources. Once the impacts of biocontrols have been valued, weighing those values against programmatic costs is the next logical step in evaluating their use. Economic methods including benefit–cost analysis, cost effectiveness analysis, and optimization frameworks are all lend to evaluating efficient use of resources.

Benefit–cost and return on investment analysis

Within the existing literature, benefit–cost analysis (BCA) is the most used to evaluate biocontrol programs. BCA outcomes are measured in terms of net benefits (total estimated benefits of a program compared to total costs) or benefit–cost ratios. BCAs are conducted both *ex ante*—prior to biocontrol release to estimate potential benefits from a proposed program—and *ex post* to evaluate an existing biocontrol program. Much of the literature we reviewed conducted *ex post* BCAs. An important step in designing a BCA is identifying the relevant stakeholders and quantifying impacts (costs and benefits) of a program. It is important to point out here that how stakeholders are defined—which benefits and who they accrue to—are influential in the results of a BCA. If a select group or one industry is included in a BCA rather than many groups of affected stakeholders, economists often refer to this as an accounting exercise because the economic opportunity costs allocating resources to program cannot be evaluated. Temporal and spatial scales are important assumptions to note in these frameworks. In the next paragraphs, we provide examples from the existing literature for how impacts and values of biocontrol have been used in BCA frameworks.

In some cases, values used in BCAs can be taken from results of other analysis such as CGE models or input–output analysis. For example, Hinz and Williams (2016) use the results of the input–output analysis conducted by Bangsund et al. (1999) that estimated the economic benefits of using biocontrol of leafy spurge in terms of increases to forage available to livestock, wildlife-related recreation, and soil and water conservation benefits in the northern Great Plains, USA. Hinz and Williams (2016) generated projected 50-year benefit:cost ratios by combining the results of the input–output analysis with the estimated cost of the leafy spurge biocontrol program in Canada. The authors used two discount rates–a tool to aid in representation of time preferences and the fact that the value of money changes over time–(5% and 15%) to present a low and high estimate for the BCA.

Some BCAs are parameterized using data that tested or documented the effectiveness of biocontrol agents in experiments or in the field. Alvarez et al. (2016) conducted a BCA of a biocontrol for Huanglongbing (Citrus greening disease) in Florida, USA using field experiments to compare the costs of pesticide inputs to orange production with and without biological control. They found that using biological control was not sufficiently effective at controlling the target species and therefore did not always create cost savings. Similarly, some of the case studies in Cock et al. (2015) use data from existing studies on changes in target species populations or yields due to biocontrol, while other cases were constructed using assumed biocontrol success rates or changes in quantities of crops brought to market. One common discussion point across analyses is the lack of information on target species and biocontrol outcomes needed to conduct evaluations, making assessing the impacts of the program a challenge (Nordblom et al. 2002, Odom et al. 2003, Fenichel et al. 2010, Marten and Moore 2011, and van Driesche and Heinz 2016).

In the absence of field data to parameterize assessments, several BCAs turned to mathematical population models to simulate biocontrol interactions with target species. Frid et al. (2013) estimate the likelihood of success of different target species management options including biocontrol programs for three weed species in British Columbia using a predator–prey model. Given realistic parameters of the target species and controls, they identify scenarios under which biocontrol will likely be most effective in controlling each weed. Cacho et al. (2022) used a mathematical model to evaluate the potential for biocontrol of the European wasp (*Vespula germanica*) in Australia parameterized using field and experimental data from New Zealand. The authors use the model to evaluate the benefits of biocontrol and the minimum values for key parameters for the program to successfully manage the pest. Wainger et al. (2018) develop a spatio–temporal model of water hyacinth (*Eichhornia crassipes*) spread in Louisiana, USA, parameterized using data from government agencies and private businesses. It is important to note that these mathematical modeling frameworks differ from economic optimization models (discussed below), as they do not solve for the efficient allocation of management resources.

A different type of economic assessment is a return-on-investment (ROI) analysis, where the cost of research and development of the program are subtracted from the estimated value of biocontrol. In our review, these analyses consistently conclude that the biocontrol programs are cost-saving, which is not surprising since the investment in developing the program is a one-time cost, while the benefits accrue annually. Pickett et al. (1996) and Paine et al. (2015) evaluate the benefits of biocontrol programs to protect urban tree species from target species in California, USA by comparing the value of replacing urban trees with expenditures on program development. Mhina et al. (2016) also quantify the ROI of biocontrol of mole cricket species in Florida, USA. While determining the ROI for a specific biocontrol program is important to illustrate potential benefits over traditional pest management practices, caution should be used when using ROI values to justify the use of biocontrol. For example, proper accounting for all investments made in creating a biocontrol program prior to implementation (sunk costs) should be included in the analysis, but are difficult to quantify and obtain. Another aspect to include in analysis or at least present as a caveat to the results of the ROI analysis are uncertain or unforeseen future program costs.

When interpreting or using the results of a BCA or ROI, it is important to carefully review the details of each analysis and their assumptions. Each BCA requires defining affected stakeholder groups, defining and quantifying costs and benefits, and assuming time horizons and parameters that affect the results (Boardman et al. 2018). For example, in the evaluation of biocontrol programs for water hyacinth, De Groote et al. (2003) reported a benefit–cost ratio of 124:1, Wainger et al. (2018) reported a benefit–cost ratio of between 34:1 and 2.9:1 depending assumptions, while Fraser et al. (2016) reported benefit–cost ratios ranging from 0.52:1 to 7.98:1. In addition to differences in geographic location of study, the variation in the authors' results can be attributed to how biocontrol impact and value are defined and measured in each assessment. Since benefits have been defined differently across the three analyses, the appropriate non-market valuation methods used to monetize impacts also differ. De Groote et al. (2003) used a survey method to quantify the impact of water hyacinth, which included transport, fishing, health, and water supply in Benin. Wainger et al. (2018) defined impacts as the change in value to recreational fishing, boating, and tourism in Louisiana, USA. The benefits in Fraser et al. (2016) were water savings and value added to irrigated crops in South Africa.

We would also like to emphasize the importance of other assumptions required when designing BCAs. We will continue to use the BCAs conducted by De Groote et al. (2003), Fraser et al. (2016) and Wainger et al. (2018) on water hyacinth to serve as examples. First, the time horizon, or the length of time considered in the analysis, across the three assessments of water hyacinth cited above were 20 years, 38 years, and 23 years respectively, implying net benefits are summed for different durations, changing the overall sum of benefits. Second, in a multi-year BCA, the assumed discount rate should be scrutinized. The discount rate is a conversion of future monetary values into their equivalent present value, implying that for various reasons the value of money changes over time. The choice of discount rate can have significant implications for BCA results. The following shows variation in rates with corresponding benefit–cost ratios in parentheses: Wainger et al. (2018) assumed a discount rate of 0% (124:1), 3% (6.8:1) and 7% (2.9:1). Fraser et al. (2016) ran their analysis using 5% (7.98:1) and 10% (0.52:1). Here, one can observe how a change in the discount rate—a single number—can significantly change the BCA outcome while holding all other assumptions constant. We emphasize these points as a caution when using BCAs or other valuations in further analysis or recommendations. Without evaluating validity of values and valuation methods (e.g., recreation value, crop sales, water), time horizon, and discount rate, interpretation of results can be flawed. With the availability of databases such as Invacost (Diagne et al. 2020)—a database of existing valuations of economic costs of invasive species—further cost or cost-savings estimates are more achievable. However we caution pulling numbers from databases such as Invacost without understanding assumptions made in the original studies, as this is a requirement for further analyses to be sound (Hulme et al 2024).

Economic models

Beyond BCAs, other economic optimization models can be used to design policy and investments of management, and are especially useful in the absence of data and *ex ante*. These frameworks maximize benefits or minimize costs while factoring a program budget constraint and biological and socio-economic factors. Mathematical bioeconomic models provide insight into the trade-offs of specific management decisions or inform on outcomes of a management program's actions. The term "bioeconomic" implies that the model contains some representation of the biophysical system and a management or decision framework for allocating resources to control the target species, typically using optimization or simulation models. The intent of bioeconomic models is to create simulated scenarios using different ecological or economic assumptions to aid in policy, practitioner, or management decisions.

Bioconomic models can be particularly useful in the case of uncertainty in outcomes and limited data. Two related methodologies applied often to the analysis of invasive species management are dynamic optimization and stochastic dynamic models (see for example Epanchin-Niell and Hastings 2010; Epanchin-Niell and Wilen 2015; Epanchin-Niell 2017). Dynamic optimization is a mathematical framework used to assess how resources should be allocated in management over some time horizon. Dynamic optimization aims to maximize a objective or value function—usually a function of the net benefits from a management program—by choosing decision variables (e.g., amount or timing of chemical treatments, biocontrol releases) where the levels of the decision variables are optimized in each time step of the model. Optimization models allow for evaluating the trade-offs of choosing different ecological and economic objectives over time.

Stochastic dynamic optimization models incorporate elements of randomness or uncertainty of variables (e.g., establishment or effectiveness of biocontrol agent) into the decision framework, adding an important aspect of reality when making decisions about management programs without having complete information or knowledge of the future. Marten and Moore (2011) develop a stochastic dynamic simulation model that provides insight into the most efficient use of biological and chemical control strategies in the case of the hemlock wooly adelgid (*Adelges tsugae*) in the USA. Using biological relationships between the target species and biocontrol and a stochastic process, their model informs how to use combinations of chemical and biological controls to manage target species effectively, where chemical treatments can negatively impact the biocontrol efficacy. The results include a two-dimensional figure with target species population on one axis and the biocontrol population on the other, illustrating for all combinations of pest and biocontrol populations which actions should be taken—no control action, application of chemical controls, release of biocontrol agents, or both biocontrol agent releases and chemical control—to maximize the benefits of the program. This paper is an example for how economic models can aid in making decisions about the most effective actions to take when facing a certain level of invasion and biocontrol agents. Economic models can also represent more complex relationships between target species, biocontrol, and human well-being. McLeod (2004) and Sinden et al. (2011) provide key examples from Australia such as the cane toad biocontrol for the scarub beetle.

Spatially explicit economic optimization models have been developed to explore both the spatial and temporal dimensions in optimal resource use. These models are especially valuable when landscape heterogeneity is critical to model results, as shown in Albers et al (2010). These models can be data intensive and computationally challenging to solve but can provide realistic insight for managers who face challenges of public/private land ownership, uncertainty in where to perform the management, or environmental feedbacks (Albers et al. 2018). Generally the findings of this literature are that recommendations for control are dependent on ecological factors of the system (Epanchin-Niell and Hastings 2010).

Designing biocontrol monitoring programs

A parallel literature in economics can guide investments in monitoring target species and biocontrol, potentially providing data and informing future assessments of biocontrol programs. For example, while not specific to the context of biocontrol, Springborn et al. (2016) present a model analyzing optimal inspection of imports to minimize the entry of infested shipments in a dynamic setting that could be modified to inform biocontrol program design. However, intensive monitoring efforts are costly. An existing literature addresses questions related to how much to invest in specific monitoring activities, which may include monitoring by the public or private entities. Epanchin-Niell et al. (2012), Holden et al. (2016), and Moore and McCarthy (2016) are just three examples that develop models that minimize the costs of surveillance and monitoring programs or maximize the benefits of a monitoring program subject to a budget constraint. Generally, this literature finds that greater investment in monitoring pays off when target species damages are high, reestablishment rates are high, and the monitoring protocol is not complex.

Gaps and challenges in existing work

Integrating economics into the planning and assessment of biocontrol programs can improve decision-making related to the use of biocontrol programs. The largest body of work has evaluated economic outcomes of biocontrol programs. However there are still knowledge gaps, from understanding the ecosystem impacts of target species and biocontrol programs and optimizing or prioritizing programs. In this section, we use the existing literature to highlight common themes in data gaps, challenges, and discussion points noted by authors of assessments of biocontrol programs.

The published literature tends to assess the direct impacts of biocontrol programs. Most assessments do not account for how it is important but difficult to measure ecosystem services that indirectly affect human well-being, such as pollination. Many analyses acknowledge this as a shortcoming of their assessment (see De Groote et al. 2003; Letourneau et al. 2015; Paine et al. 2015; van Driesche and Heinz 2016; Valente et al. 2018; Wainger et al. 2018). Consequently, the estimated benefits of biocontrol agents are likely low. To better comprehend the value of biocontrol and healthy ecosystems, it is necessary to continue to investigate and attempt to understand these indirect biological or ecological impacts.

Even when economic analysis is comprehensive and considers multiple benefits of managing the target species (e.g., Paula et al. 2021), there is no standardized framework for defining and valuing impacts of biocontrol. In addition to acknowledging differences in heterogeneities between locations driving changes in program value, differing economic frameworks used in assessments, sometimes of the same biocontrol program, pose challenges to direct comparisons of results or further recommendation of specific biocontrol agents. In the section above we discussed three BCAs that assumed different values and discount rates for control of water hyacinth. In subsequent work, which BCA results should be used? Clearly if one is interested in promoting the future use of biocontrol, the highest benefit:cost ratio would present a most convincing case. However, what are the consequences of cherry-picking values or re-citing BCA results without providing disclaimers about assumptions?

Conducting economic assessments is complicated by data limitations, making it difficult to accurately quantify the many cause-and-effect relationships that connect management actions to their benefits and costs. The adage "you can't manage what you don't measure" applies here, especially given the scarcity of data surrounding the population dynamics of target species (Nordblom et al. 2002; Marten and Moore 2011; van Driesche and Heinz 2016; Maluleke et al. 2021). For some long-established target species, decades of observations about the presence, spread, and severity of invasion serve as a baseline for assessing the effectiveness of biocontrol agents (McLeod 2004; Sinden et al. 2011). However, for other target species, little is known about the extent of the baseline or current invasion, making it more challenging to estimate the extent of damages from the target species or biocontrol success.

Furthermore, public availability and access to invasion data are limited and may not be collected or shared in a standardized format, restricting the ability of researchers to develop research questions and formal methodologies based on existing knowledge. According to Schwarzländer et al. (2018), the ability to determine the effectiveness of biocontrol systems was limited to analysis conducted by regional weed control experts who had additional information about the invasion and control that were not published. Access to full information about the costs of biocontrol programs is another limitation to future work. While some assessments gained access to grant funding and salary expenditures used to develop biocontrol programs, program implementation and monitoring costs were not included in the calculation of ROI. Such costs are elusive and inconsistently documented, despite their importance for evaluating management efficiency, projecting future control program costs, and prioritizing conservation efforts. To address this, Iacona et al. (2018) have proposed a framework to formalize cost reporting. However, even with such frameworks available, cost data may still be unreliable due to a lack of resources or national socio-economic and institutional factors. Overall, the lack of essential data means that current economic analyses rely heavily on assumptions and sensitivity analysis limiting their value in decision making.

The difficulties of data availability and reliability become more pronounced when there are significant indirect benefits, such as improved water quality, human health, and flood control, creating additional challenges in program assessment. The inherent complexity and interconnectedness of ecosystems can make it difficult to map the impacts to values. As previously discussed, quantifying non-market impacts is notoriously challenging due to their indirect nature and the lack of market prices to establish their value. We find that studies incorporating non-market valuation predominantly occur when evaluating biocontrol in natural areas, temperate forests, and urban/semi-urban environments (Odom et al. 2003; Marten and Moore 2011; Richter et al. 2013; Liao et al. 2016; Isely et al. 2017). These papers exhibit a diverse mix of economic methods, including hedonic modeling, dynamic optimization, and stochastic dynamic programming. This diversity is primarily due to the non-market nature of the measured impacts, which are inherently more varied and complex in these environments than in more homogeneous and well documented agricultural settings. It is imperative to continue to develop and employ the methodologies and frameworks in "Economic evaluation of biocontrol programs" and "Frameworks for assessment of biocontrol programs" that can effectively map ecosystem services to their impacts on human well-being and quantify these values, ensuring a more comprehensive evaluation of biocontrol programs.

Enhancing economic analyses of biocontrol programs

Biological control agents show considerable promise in target species mitigation, reducing pesticide reliance, and enhancing ecosystem health. Yet, a comprehensive understanding of their benefits and trade-offs demands rigorous and nuanced assessments. Currently, most studies assessing biocontrol programs are conducted predominantly by experts within the natural sciences, potentially omitting valuable insights from socio-economics. Bringing economists and social scientists into the conversation around how to plan and evaluate biocontrol programs could significantly increase capability to measure and accurately value their benefits. Below we highlight future research directions and priorities for researchers and practitioners to expand the economic analysis of biocontrol.

Most critically, data availability and information sharing concerning target species, biocontrol agents, and integrated pest management or biocontrol programs must be prioritized. The establishment of baseline and monitoring datasets for target species and their biocontrol agents is not only fundamental but should be an inherent part of any rigorous evaluation, whether economic or otherwise. Given that many biocontrol programs are government-driven initiatives, it is imperative that management agencies and funding sources mandate the inclusion of comprehensive plans for monitoring and data sharing. This should encompass program objectives and progress, ensuring transparency and accountability. Citizen science exhibits some promise in expanding data availability. Tools like the National Institute of Invasive Species Science's (NIISS) "living maps" database Apps such as iNaturalist (https://www.inaturalist.org) and Outsmart Invasive Species (https://masswoods.org/outsmart), have the potential to offer real-time tracking and mapping of target species. These resources can be leveraged effectively to strengthen monitoring and evaluation programs. There are challenges that citizen science resources pose, including concerns about data completeness and verification. However, continuous development and validation of these tools can significantly enhance their utility in the realm of scientific assessments, thereby bolstering the effectiveness of biocontrol programs and improving our understanding of their economic and ecological impacts.

One area for research improvement concerns setting clear objectives for biocontrol programs or metrics for program evaluation that can then be evaluated. To alleviate this issue, Hoffmann et al. (2019) proposes a conceptual framework for characterizing biocontrol program outcomes as a function of its effect on the target species. In this article they also discuss important details such as accounting for spatial heterogeneity in measuring and evaluating control success.

Biocontrol outcomes may fluctuate across seasons or years, so attention should also be paid to estimating the long-term or inconsistent year-to-year impacts. The necessity to monitor and reintroduce biocontrol agents in some years adds another layer of complexity to the economic analyses. Temporal variability in biocontrol agents' effects was rarely discussed in analyses we reviewed. Short-term studies might fail to fully capture broader regional and temporal impacts, and vice versa. Another challenge lies in the perpetual risk of non-target effects of biocontrol agents over time, which may lead to unintended ecological consequences (externalities) (e.g., Paula et al. 2021). The interaction of biocontrol agents with existing ecosystems could lead to unforeseen results that are challenging to incorporate into economic evaluations and continues to highlight the need for more field and observational data. A related but often overlooked assumption in biocontrol assessments is that co-evolution maintains consistent interaction levels between host and parasite, thereby preventing a gradual reduction in the effectiveness of the biocontrol agent over time (Smith et al. 2010). As the target species population declines the biocontrol population likely will as well, which introduces questions about long-term dynamics and the self-sustaining nature of programs.

As economic analysis of biocontrol evolves to inform management decisions, it is important to consider whose benefits and costs are captured and weighted in assessments. This can lead to potential environmental justice concerns, as the distribution of benefits and costs may vary across communities and stakeholders. Current biocontrol policy evaluations generally occur in more affluent countries and regions (Cock et al. 2015), so it is unclear how biocontrol benefits and costs are distributed across different populations. Additionally, in terms of benefits, while most pests discussed in this paper are associated with ecological harm, some may yield secondary benefits that should be included in comprehensive impact analyses. For example, Higgins et al. (1997) discuss the loss of firewood sales from reducing an invasive tree in Africa. In terms of funding for biocontrol programs (if through taxes, for example), a better understanding of who pays and who receives the benefits is an important consideration in evaluating the well-being implications of biocontrol. When conducting a BCA, it is up to the analyst to define the relevant stakeholders and tally the costs and benefits which can be subjective or limited in scope (e.g., just focusing on the direct benefactors of the biocontrol program).

Considering use of a social welfare function could be an improvement over existing analyses, which consider the benefits or costs to a small group of stakeholders or single industry. A social welfare function is a theoretical concept or mathematical formula used to assess and aggregate the well-being or welfare of individuals within a society (producers and consumers). Social welfare functions aim to determine the overall or collective welfare of a society based on the well-being or utility of its individual members. They typically consider factors like income, wealth, health, education, and other elements that contribute to people's quality of life. The function assigns a numerical value to each possible distribution of these factors and helps policymakers to evaluate different policy options. The choice of a social welfare function is often a matter of debate and depends on the ethical and political values of a society. Different functions may prioritize equality, efficiency, or other objectives. One common social welfare function is the utilitarian approach, which seeks to maximize the total sum of individual utilities or happiness. In practice, social welfare functions can be used to evaluate the impact of policies, such as taxation, social programs, or environmental regulations, and help policymakers make decisions that balance various societal goals and values.

Economics contributes to understanding the complex nature of biocontrol policies, often integrated with other methods such as chemical or mechanical treatments within a larger management plan (i.e., integrated pest management) (Naranjo et al. 2015). A standard definition of integrated pest management is a systems approach integrating soil, water, flora, fauna, time that may enhance the abundance and activity of existing natural protectors (e.g., predators) of potential target species in settings such as agriculture and forest ecosystems. Naranjo et al. (2015) provide a review of the economics of integrated pest management literature in North America including biological control noting benefit–cost analysis and valuation efforts to compare biological control with other options for addressing arthropods as target species. Two studies from the USA offer examples of quantitative analysis from that literature. Cooper and Keim (1996) conduct a statistical analysis to evaluate the potential to meet multiple objectives including target species management through the USDA's Water Quality Incentive Program with a dataset representing Midwest and Eastern states. Park and Lohr (2005) utilize a national database in a statistical analysis of target species management incentives through organic farming. Both econometric publications utilize a limited dependent variable approach to distill which factors (e.g., policy incentives, farmer socio-economics, biological) contribute to adoption of management practices.

Conclusion

Biocontrol programs are an important tool in managing undesirable species. Economists, with their expertise in optimizing decision-making have the potential to significantly contribute to biocontrol science and policy. Through modeling and empirical analyses, economics has more to contribute than just benefit–cost exercises. To engage economists in future work related to biocontrol programs, we define four priorities for researchers and managers: (1) Broaden the availability of information on existing and planned biocontrol programs—especially focusing on program objectives. (2) Provide data, either experimental or in the field about interactions (e.g., biological parameters, search time, predation or parasitism rates) between target species and biocontrol agents in order to consider spatial and temporal impacts of biocontrol agents on target species. (3) Identify and measure how ecosystem functions and services are impacted by pests. (4) Recognize that both the science of biocontrol and the context of socio-economic and institutional settings in which biocontrol is used determine the overall success of a biocontrol program. Addressing these areas will elevate future economic analysis of biocontrol, leading to more informed research, biocontrol programs, and management.

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Ethical approval We follow the rules of good scientific practice. The article is original, complete, and not in concurrent publication. The results are clear, honest, and not fabricated or falsified. There is no plagiarism. We cite appropriately. We avoid untrue statements about an entity. Our research does not pose a threat to public health or national security, and authorship order is correct and all authors consented to the submission.

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Katherine Lee is an associate professor at the University of Idaho, USA. Her research uses mathematical models, combining economic and ecological theory, and empirical analysis to explore feedbacks between resource management decisions, environmental outcomes, and human well-being.

Shana McDermott is an associate professor at Trinity University, USA. Her research focuses on jointly determined human and natural systems, and developing policies that will enable humans to better manage natural resources.

Linda Fernandez is associate professor of environmental and resource economics at Virginia Commonwealth University, USA, in the Department of Economics and Center for Environmental Studies. Her research explores public and private economic incentives for pollution abatement and natural resource protection at local through international scales. Her research findings have been used to inform policymakers at state, national and international levels of governance.