The Economics of Integrated Pest Management of Insects

David W. Onstad
and **Philip R. Crain**

CABI

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To Dawn, Nora and Emma
David’s WTP is infinite.

To my wife Emily, and kids Beckham, Benson and Morgan. You’re the inspiration for all my work.
Also to my dad, Danny, and in remembrance of my mom, Brenda.

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Preface

This book developed from a symposium that we organized for the International Congress of Entomology in 2016. Although many of the authors of these chapters spoke at the symposium 'Economics of IPM in the 21st Century: Multiple Perspectives from Around the World', we asked a few other scholars to contribute to the book to ensure that our coverage of this topic was comprehensive. We thank all the authors for believing in our goals and trusting us to lead them in the right direction.

We developed both the symposium and this book because we believe that economics of management has been de-emphasized by most funding agencies and during most entomological activities. However, we are optimistic that entomology and economics can provide valuable support to the next generation of IPM practitioners and IPM-conscious growers and decision makers. The knowledge presented by the authors within this book will prove invaluable to those who seek to improve IPM as a public service and good.

We thank Ward Cooper and CABI for believing in our mission to promote economics in IPM. We thank our editors at CABI, Tabitha Jay and Marta Patiño, for helping us produce the book. We also thank Rod Rejesus, Terry Hurley and Paul Mitchell, who have always been kind enough to explain the techniques, practice and philosophy of economics. Philip thanks Michael Rizzo for providing him with a grounding in economics. David thanks his colleagues at the Department of Entomology at Iowa State University for offering him a second scientific home in Iowa.

1

Major Economic Issues in Integrated Pest Management

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Most readers of this book will know the dominant paradigm in pest management, particularly insect management, called integrated pest management (IPM) (Kogan, 1998). Many, however, will have only a vague notion about economics. Although Kogan (1998) concluded that cost–benefit analyses should be the basis for IPM strategies, the role for economists or economically savvy entomologists is often unclear. Certainly, economics is concerned with costs, profits and money. But even more fundamentally, economics accounts for human values, especially those that can be measured, in efforts to explain production and consumption of goods and services.

Entomologists will recognize our own consideration of human values when we define pests. An arthropod is a pest in situations (places and times) in which a human stakeholder (i) is harmed by it, (ii) loses benefits because of it or (iii) even just does not like it. An insect can be considered by humans to be positive or beautiful in one setting, but a pest in another, simply because of human values. For instance, European honey bees (*Apis mellifera*) are generally regarded as good for their honey and pollination services. But they are considered pests if the hive is too close to people afraid of bee stings or if their invasiveness disrupts native ecosystems. Fundamentally, the willingness of people to pay for honey, pollination or removal of bees, in essence their values concerning bees, determines how these insects will be managed. How many jars of honey would someone accept in exchange for a hive being placed near her home? Would the production of 10 million jars of honey be enough to compensate a community for accepting the risk of endangering populations of wild pollinators? An economist can help people (stakeholders) clarify and measure their values and use this information to decide how to allocate resources to manage common or potential pests to satisfy multiple objectives in their lives and businesses (National Research Council, 1999, 2005). Halasa-Rappel and Shepard (Chapter 2) and Dickinson *et al.* (2016) describe how the measurement of human values (economic valuation) can be used to allocate public resources to provide services that improve health and leisure in a community affected by mosquitoes.

Measurement of values, even straightforward monetary ones, is not easy (National Research Council, 1999, 2005). However, it is a necessary beginning. Zalucki *et al.* (2012) provide an example of first steps needed to understand the economics of a pest at geographic scales considered by policy makers, regulators, funding agencies or any other stakeholders focused on national IPM. They determined that the management of *Plutella xylostella*, a global pest of *Brassica* species, involves US$4–5 million in annual control costs and crop losses. For Brazil, Oliveira *et al.* (2014) estimated the total annual economic losses caused by insect pests infesting crops to be ~$17.7 billion. Oliveira *et al.* emphasized the need for new and improved data regarding the losses caused by insects and the need for systematic monitoring of these losses.

Oerke (2006) estimated the potential and actual losses of harvested crop yield for animal pests on six crops worldwide for the period 2001–2003. Animal pests include arthropods, nematodes, snails, slugs and vertebrates. The potential and actual percentage losses were: wheat (8.7, 7.9), rice (24.7, 15.1), maize (15.9, 9.6), potato (15.3, 10.9), soybean

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(10.7, 8.8) and cotton (36.8, 12.3). The actual losses occur even with efforts to protect the crop. Thus, for these six field crops, typical pest management seemed to be most effective for rice and cotton and least effective for soybean and wheat. Oerke (2006) also estimated the value of pest management in 2001–2003 by comparing the potential and actual losses due to animal pests by evaluating the monetary production losses for barley, cottonseed, maize, oilseed rape (canola), potato, rice, soybean, cotton, sugarbeet, tomatoes and wheat. Oerke found that pest management reduced losses by 39% worldwide.

Economic loss due to pests (including such organisms as viruses as well as arthropods) in livestock has been estimated at nearly $9 billion annually (Pimentel *et al.*, 2000). Looking specifically at insects, key pests, such as the stable fly *Stomoxysis calcitrans*, result in annual losses in the order of $2.2 billion to the cattle industry through reduced weight gain and decreased milk production in the US alone (Taylor *et al.*, 2012). Economic loss due to this pest is significant in many other countries including Brazil (Grisi *et al.*, 2014) and Mexico (Rodríguez-Vivas *et al.*, 2017). In addition, livestock entomology has seen great success in controlling *Cochliomyia hominivorax*, the New World screwworm, using mass releases of sterile male insects (Vargas-Terán, 2005). In this example, the cost of implementation between 1958 and 1986 was high, estimated at $650 million in 2005. But, the economic benefits exceed $890 million annually in the US alone and greater than $1 billion dollars worldwide.

Similar to the cattle industry, the sheep industry has multiple markets for its products. In New Zealand, the sheep blowfly, *Lucilia cuprina*, was introduced in 1988 and resulted in an increase in the cost of fly control to $37 million annually for sheep farms with only 3–5% of the flock infested (Heath and Bishop, 1995). Sackett *et al.* (2006) estimated a cost of $280 million annually to control flystrike. Lice also caused significant costs greater than $100 million. McLeod (1995) estimated the cost was $161 million and $169 million, respectively, for the sheep blowfly, *Lucilia cuprina*, and various sheep lice, *Linognathus pedalis*, *Linognathus ovillus* and *Bovicola ovis*.

Insects are also important to human health and are disease vectors for many of the most important diseases humans face. In 2017, malaria infected more than an estimated 200 million people causing ~445,000 deaths worldwide (World Health Organization, 2017) causing an estimated $12 billion loss to Africa every year (https://www.malariafreefuture.org/malaria). The number of cases has increased over the past few decades, but case mortality has decreased compared with a study from Hammer (1993) claiming 100 million infections with 1–2 million deaths annually. A report on the economics of malaria control by Hanson *et al.* (2004) showed the cost effectiveness of different control tactics and found inexpensive ways to reduce malaria incidence include limiting transmission of disease from mother to child, improving current case management and use of insecticide-treated nets. Other insect-vectored diseases cause significant mortality and morbidity to humans such as Dengue fever, affecting over 100 million people annually (Racloz *et al.*, 2012), Chikungunya virus, Chagas disease and Zika virus. Therefore, the economic cost of disease control is very significant globally. The economics of vector control is an interesting case because utilizing aggressive treatment tactics against vectors early may result in more sustainable long-term control of diseases (Oduro *et al.*, 2018).

Several economists have urged caution in applying simplistic approaches to determining the value of insect control tactics (Lichtenberg and Zilberman, 1986; Lichtenberg *et al.*, 1988; Zilberman *et al.*, 1991; Carrasco-Tauber and Moffitt, 1992; Chambers and Lichtenberg, 1994; National Research Council, 2000). Norton and Mullen (1994) produced a good early summary of the economic value of IPM programmes in the US. They reviewed 61 studies of IPM programmes in cotton, soybean, vegetables, fruit, groundnut, tobacco, maize and alfalfa performed over the previous 20 years. The emphasis of most was on field- and farm-level budgeting of IPM alternatives, particularly the use of sampling and economic thresholds to make decisions about pesticide applications. Although pesticide use declined on average for seven out of the eight crops or crop types, 21% of the 61 studies found increased use of pesticides with the adoption of IPM programmes. Before 1994, IPM actually increased the average use of pesticides in corn production in the US (Norton and Mullen, 1994), but it is unclear whether this was mostly for weed, insect or pathogen control. Maize (*Zea mays*) production changed dramatically after 1994 with the introduction of transgenic insecticidal traits (Bt maize) to manage key insect pests. For the field crops and fruits evaluated, net returns per hectare had an average 48% increase with IPM programmes. The two extremes were tobacco with only a 1% increase and groundnut with a 100% increase. In this book, Rejesus (Chapter 3) and Norton *et al.* (Chapter 8) describe newer studies that evaluate the value of IPM programmes around the world.

Basic Economics of Management

At the beginning, we stated that economists start their work by measuring the value of goods, services and even things that are often not easily recognizable as either, such as health, safety or a good environment. When goods and services are exchanged in economic markets prices are set by supply and demand, and entomologists and economists have an easier time determining the values that stakeholders place on most things, at least for most purposes considered relevant to pest management. However, not all important resources and ecosystem services are exchanged in markets. Furthermore, market prices do not always account for externalities that impact resources and ecosystem services beyond the exchanged good or service. In these two cases, economic valuation must determine what people are willing to pay for goods, resources and services not available in a market. How much are people willing to pay for pollination services by wild insects? An answer to this question determined by economists through surveys can then help decision makers decide how much to spend to protect these pollinators.

But what do economists expect to do with this information? In *positive economics*, economists describe what is happening in a system of transactions. However, with n*ormative economics*, economists identify what ought to be, given the goals of stakeholders. Traditional economics typically assumes that stakeholders are rational in some ideal sense, whereas in behavioural economics, the ideal assumptions are relaxed and the models and analyses account for more realistic and complex human behaviours. Most analyses described in this book fall under the category of rational economics, but one theme of this book is the exploration of the complications that human behaviour beyond simple transactions bring to IPM (Musser *et al.* 1986).

The word ‘management’ in integrated pest management implies that a decision must be made by a stakeholder who has a stake in the outcome of the pest management. Many decisions are made based on a formal or informal economic evaluation. Even decisions based on a vague description of convenience can be associated with the economics of time use and labour. Some believe that entomologists have lost the focus on management or at least the economics that forms the basis for management (Mitchell and Hutchison, 2009). Note that not all economic studies are performed to influence management, but most retrospective or predictive analyses described in this book were meant to affect decisions and therefore management. Retrospective studies are almost always empirical: the 2-year field experiment or the analysis of large-scale data over the past 10 years. To influence decision making after the retrospective study, the assumption is made that the past can represent the future in some way or that the few fields studied represent all fields in a region. In predictive studies, we assume that we can know much about the future – or at least enough about the future to make better predictions with an economic model than we would without the model. Thus, in both retrospective and predictive cases, we make assumptions and hope that they are reasonable.

Every economic analysis of systems being managed to limit the influence of pests must define four factors. First, the stakeholders and the perspective taken in the analysis must be determined. Then the goal of the analysis must be clarified to match the perspective of the stakeholder. Third, the time period (temporal scale) for the analysis must be chosen. Fourth, the spatial scale or extent must be defined. Furthermore, when modelling is performed, the system is defined to include some possible components and exclude others. By system components, we mean the organisms, resources and practices that represent the public health, urban or agricultural system. Note that the temporal and spatial scales and the dimensions of the system are subjective choices that should always be justified based on logic, financial constraints and the information available.

Each IPM-related economic problem has stakeholders that interact for the purposes of commerce, food production or public health. Farmers, government agencies, private companies, universities, consumers and others can be stakeholders in an economic analysis. Usually, the number of stakeholders is minimized to make the problem simpler to solve and to focus on decisions made by only one or two stakeholders. Society and social welfare are often used by economists to substitute and simplify all the stakeholders existing in a large system of production and consumption. However, entomologists and economists may want to take the different goals of several stakeholders into consideration when evaluating solutions derived from simpler analyses.

The time period for the economic analysis is defined by the time horizon. For *ex-ante* economic analyses involving predictions of future costs and benefits arising from current decisions, subsequent activities must have a subjectively selected time horizon. The time horizon must be justified as the endpoint for the time-discounted economic analysis. It can also be thought of as the endpoint defining the period during which a stakeholder will evaluate resource management decisions. If the economic analysis is for 1 year or season, then this has a 1-year time horizon. Typical time horizons for stakeholders concerned about managing insect resistance to insecticides, host-plant resistance, crop rotation, mating disruption and other tactics putting strong selection pressure on pests are 10–20 years (Onstad and Mitchell, 2014). Longer time horizons may also be preferred by stakeholders promoting classical biological control and other IPM approaches that redesign the agricultural or public health system (see section on 'System Design' below). All resource values after the time horizon are ignored as either too small (discounted too much) or irrelevant to the stakeholder (Mitchell and Onstad, 2014).

Entomologists often consider distant time horizons in conceptual discussions, but rarely know how to incorporate these time horizons in rigorous evaluations of IPM. Another theme of this book is the demonstration of long-term analyses and the encouragement of their use by entomologists.

Because people tend to prefer immediate rewards over delayed rewards, particularly those delayed several years, *ex-ante* or predictive analyses use time discounting to reduce the value of future costs and benefits and calculate the present value. The present value or net present value (NPV) is commonly used in decision making in the present that accounts for the long-term consequences of a strategic plan. Financial markets use discount rates to determine the price of assets with future value. The discount rate is similar to the interest rate for a savings account in a bank. Mathematically, the discount rate r per year determines the discount factor f that converts a future cost or benefit into an equivalent present value: $f(t) = [1/(1 + r)]^t$, where t is the number of years in the future. In the 10th year, the discount factor is 0.74 and 0.51 for discount rates of 0.03 and 0.07, respectively. In the 20th year, the discount factors decline to 0.55 and 0.26, meaning that a stakeholder will consider \$100 in the 20th year the same as \$26 to \$55 in the present when making a decision. Thus, as r increases, for instance from 0.03 to 0.07, future values are discounted more strongly and the decision maker places less emphasis on, or has less concern for, the future compared with the current year.

Mitchell and Hutchison (2009) and Mitchell and Onstad (2014) describe a variety of techniques used to evaluate the economics of IPM. The most frequently used method for evaluating alternatives for pest management is budgeting analysis (Norton and Mullen, 1994). Enterprise budgeting is a listing of all income and expenditures related to an activity to provide an estimate of profitability. Usually these are per hectare crop budgets and per animal livestock budgets that include all input costs, revenues and net returns for all production practices. Fixed and variable costs are considered. Norton and Mullen (1994) noted that one problem with enterprise budgets is that differences in farmers and farm management may not be adequately considered in a sample of farmers divided into users and non-users of either IPM or the new set of management options. Therefore, care should be taken when drawing conclusions about the groups defined for the economic evaluation. Partial budgeting is often used when more than one enterprise or major activity is changed with the adoption of new IPM. Partial budgeting is also simpler because only the benefits and costs expected to change significantly with the new IPM are accounted for. However, both kinds of budgeting analyses may overestimate the economic effects of changes in insecticide use or some other simple insect control tactic (National Research Council, 2000). These methods consider only a small subset of control options and only short-term alternatives that do not consider changes in farm design.

Another component of economic analyses is the measurement of attitudes towards risk by stakeholders. Some people and organizations are risk neutral, but many are risk averse. By risk averse, we mean that the decision maker would prefer to receive a smaller certain benefit than a larger expected benefit if there is uncertainty. Many farmers are described as risk averse in their decision making regarding insect management. However, one could say that farmers are overall risk takers due to the wide variety of climatic, financial and pest-related factors that make farming generally very risky. But Musser *et al.* (1986) have suggested that farmers do not consider risk to be important with regard to pest management. Generally, the public and government agencies are risk averse when mosquito control and public health are being evaluated. Loss aversion, greater value placed on losses than on the same magnitude of benefits, also can influence decision making (Liu and Huang, 2013).

Pannell *et al.* (2000) questioned (i) the predominant use of static frameworks to formally analyse risk; (ii) the predominant focus on risk aversion; and (iii) the idea that explicitly probabilistic models are likely to be helpful to farmers in their decision making. They concluded that there is very little value in accounting for risk aversion for the types of strategic problems most commonly modelled by agricultural economists. Pannell *et al.* (2000) believe that risk averse farmers want information and advice on how to respond tactically to dynamic pest problems. This perspective implies that integrating good strategic plans involving biological control, host-plant resistance and landscape design with advice for seasonal use of additional tactics that protect farmers from unusually high pest pressure could generally lower risk that occurs from multiple factors.

Pannell (1991) showed that uncertainty in pest density does lead to higher optimal insecticide use for risk averse farmers. However, Pannell (1991) also determined that uncertainty in other factors influencing livestock and crop production could cause a lower optimal level of insecticide use. Similar results were obtained for Bt maize adoption with benefits relative to risk dependent on a variety of factors (Hurley *et al.*, 2004). Mitchell *et al.* (2002) explored the risks farmers experience when planting refuges for insect resistance management.

System Design

Pest management consists of two types of activities that change a system so that stakeholders can achieve their goals. Most management relies upon control of inputs such as fertilizers, pesticides, release of biotic agents, harvesting, pruning and other factors chosen with timing and amounts determined based on monitoring or informal observation (Ruesink, 1976). Control tactics manipulate the labour, energy and schedules used to provide, change or remove resources from the system. In essence, if a farmer or consultant makes a decision about deploying a tactic in the middle of a pest outbreak or activity, this is control. The other option in management is designing the system: either creating a new system structure or restructuring some of the components within an existing system. We often take the system's design (structure, configuration, number of ponds, trees, plants, etc.) for granted when we propose adjusting seasonal inputs for controlling insects. Could the system be designed better to reduce the need for control or to make control more efficient? Can long-term economic benefits lead to radical system changes?

Figure 1.1 presents a conceptual diagram of how control and design influence a system (Onstad, 1985). The two central rectangles represent two possible states of the system being managed. These could be a farm, an agricultural field or a city with mosquitoes. The internal elements are different in the same sense that the physical environment of real systems may be different after restructuring land and water and any other component implemented for the long term (Onstad, 1985). Changes in arrows within the rectangles signify that flows between elements will likely change with restructuring. The arrows outside the rectangles indicate that resources flow into the systems and outputs flow away from the system. The small, double triangle marks on the arrows remind us that control adjusts the rates of these flows.

Several authors have advocated for a greater role for design in agro-ecosystem management (Caswell *et al.*, 1972; Koenig and Tummala, 1972; Haynes *et al.*, 1980; Edens and Haynes, 1982). Choices for control are obviously influenced by a system's structure. The traditional example of a design change is the selection of a crop variety based on host-plant resistance to pests (Onstad, Chapter 5). Classical biological control has been one of the most important aspects of design by adding a new natural enemy to a system requiring pest management (Naranjo *et al.*, Chapter 4). The same can be said of conservation biological control with the modification of the local environment to promote natural enemies (Naranjo *et al.*, Chapter 4). Many other components could be altered, including planting site, row spacing, irrigation network, inclusion of trap crop and crop rotation plan. In public health, cities could be designed to limit the sources of water for mosquitoes or include predators in ponds to attack larvae. In some cases, design has the disadvantages of being more difficult to implement and of not being profitable over the short term. There may be

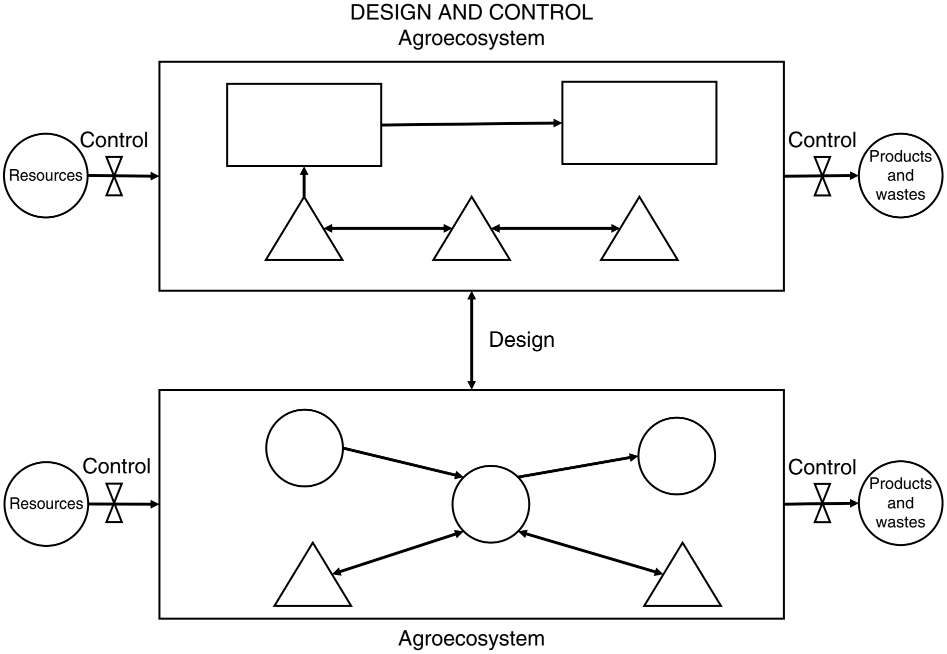

Fig. 1.1. Representation of landscape or environmental design and seasonal control of inputs and outputs as two aspects of pest management.

more opportunities for redesigning annual cropping systems than perennial ones. The economic rewards, however, are just as important with perennial cropping systems, because design usually has the advantage over control of having a greater effect over the long term (Hoyt and Gilpatrick, 1976; Westigard, 1979).

One major change in design is to convert from a conventional system to an organic or similar system. Note that organic systems must be certified by a third party to obtain the typical price premiums for organically branded products. Zentner *et al.* (2011) evaluated a variety of organic and conventional systems of field crops in Canada over 8 years. Some systems included crop rotations over 6 years. Zentner *et al.* (2011) concluded that the organic systems, several years after the certification, were more profitable as long as the organic price premiums existed. Walsh *et al.* (2011) performed an economic evaluation of an experimental orchard with apple and pear trees. Part of the orchard was managed under conventional plans while the other part was managed under organic production rules. They concluded that organic production took more time than conventional production due to the labour required for weed control and the additional pesticide applications. Benefits were estimated to be lower in the organic sections primarily because of lower organic fruit yields, with the higher expenses required for chemicals and labour also contributing (Walsh *et al.*, 2011).

Farnsworth *et al.* (2016) found that when an invasive insect is being managed, organic berry growers may not be able to recover economically as fast as conventional growers. The spotted wing drosophila, *Drosophila suzukii*, is an economically important pest that is native to south-east Asia but has become established in North America and many countries in Europe (Asplen *et al.*, 2015). Spotted wing drosophila invaded the California raspberry (*Rubus* sp.) industry causing considerable revenue losses and management costs in the first years following invasion. Few of the tactics eventually used to control spotted wing drosophila were needed to prevent injury from other pests prior to the invasion. All growers lost about 5% of revenue in the first few years. Conventional growers eliminated these losses by the fifth year by implementing effective chemical control programmes. Organic berry growers, who by design do not have access to the same chemical controls, continued to lose money at the same rate through the sixth year. They can mitigate losses only by applying expensive insecticides registered for organic use and by performing labour-intensive field sanitation.

Spotted wing drosophila prefer ripening fruit, laying eggs under the fruit's skin resulting in unmarketable fruit (Atallah *et al.*, 2015). An economic analysis by Del Fava *et al.* (2017) used partial budget analysis to investigate the expected NPV of different IPM systems. Following the invasion of spotted wing drosophila into northern Italy in 2009, a conventional IPM strategy was employed while flies were at relatively low density. However, populations continued to increase and reached much higher densities in 2014 compared with previous years. At higher densities, and damage, the system was redesigned to include exclusion nets, despite significant implementation cost. The new design achieved better management relative to the conventional IPM strategy. Examining 2 years of data (2014 and 2015), Del Fava *et al.* (2017) showed that exclusion nets ('upgraded IPM') resulted in increases of profit up to €2.5 million.

A final example for considering system redesign as opposed to simply control involves the coffee berry borer, *Hypothenemus hampei*, which challenges coffee production globally. Atallah *et al.* (2018) developed a bioeconomic model evaluating coffee berry borer control and other economic benefits associated with shade-grown coffee in Colombia. Analysis found that shade-grown coffee lowered temperatures in the microclimate inhabited by the coffee berry borer slowing development and reducing the number of generations per year. When infested by *H. hampei*, shade-grown coffee provided higher economic benefit, relative to sun-grown, but only for a range of shade (15–30% shade). In the absence of the insect or if shade was outside the optimal range, sun-grown coffee was more profitable. Additional benefits from shade-grown coffee systems include better nutrient cycling (ecosystem service) and revenue from timber. Furthermore, shade-grown coffee, when produced under certain conditions, can usually demand a price premium in many organic or sustainably grown markets. Without the price premium, rarely is shade-grown coffee more valuable than sun-grown (Atallah *et al.*, 2018). With higher premiums, the range of tolerable shade cover increases above 15–30%. As climate change increases temperature, leading to an increase in coffee berry borer generations per year and population density, evaluating different systems, such as shade-grown coffee production, may need to be considered.

Rusesink (1976) stated that control has received the attention in pest management, but he predicted that design would play a bigger role in the future. In our concluding chapter, we will summarize our thoughts about how much consideration design has received over the 40 years since Ruesink's prediction.

Economic Studies for the Major Approaches to IPM

In this section, we provide an overview of the types of costs involved in major approaches to IPM. We separate pest management into two categories (taking the perspective of a farmer): those efforts that primarily have significant annual costs and those with mostly sunk costs. Of course, other stakeholders (including society) may require different perspectives and analyses. For example, most of the costs for an insecticide are sunk for corporation but annual for the farmer. Both categories require extensive research and development prior to implementation. Benefits and costs to the farmer may be easy to determine on an annual basis, but externalities for society, both positive and negative, add complexities for different analyses. Furthermore, the descriptions below are ideal. In most economic analyses, some factors are missing.

Design changes and choices made for the long term

Classical biological control

Naranjo *et al.* (Chapter 4) provide details about many economic analyses of classical biological control and conservation of natural enemies (see section below). Most of the costs of these efforts occur before a seasonal pest outbreak. These programmes can also often provide benefits to many farmers or citizens in a region much like area-wide IPM (Koul *et al.*, 2008).

For classical biological control involving introduction of non-native natural enemies, public research and development efforts that should be included in economic analyses include foreign exploration and collection, the maintenance of quarantine facilities in the country collecting the foreign species, controlled-environment experimentation on the targeted pest and non-target organisms, mass rearing of the natural enemy before release, preliminary field studies, storage and delivery. Field evaluations after formal release should also be considered as valuable efforts worthy of inclusion in analyses.

Choice of livestock breed and crop variety

The primary decision is the choice of species to produce on a farm. The secondary selection is the animal breed or crop variety. Whether these decisions are made annually or only once every 5–10 years, the underlying costs of research and development must be considered in economic analyses (Onstad, Chapter 5). Host-plant resistance involves investments in public and private research and development. Often private investments are represented by higher costs of seed or rootstock, but the public costs are often unknown and end up being subsidies for farmers. Similar types of costs should be considered in analyses of livestock IPM. Because arthropods can evolve resistance to highly effective host resistance (Onstad and Knolhoff, 2014), the benefits of resistance in livestock and crops may decline over time.

Schedule for crop or livestock paddock rotation

A long-term schedule for rotation of crops or relocation of livestock from paddock to paddock is a good tactic to consider in IPM (Lechenet *et al.*, 2014; Khakbazan *et al.*, 2015). Economic evaluations need to be especially careful in selecting the time horizon and the spatial scale. The time horizon should account for at least one full rotation of all crops or paddocks. But this would only be one replicate. Therefore, either the time horizon must be extended to account for multiple full sets or one full set over time should be performed at multiple locations to create more replicates. If the pest disperses easily across an area with various states of the rotation or fields without rotation, then the evaluation likely must deal with this phenomenon as well.

Khakbazan *et al.* (2015) performed a 4-year field study on Prince Edward Island, Canada, to determine the economic effects of converting from conventional potato production to organically managed systems. Seven organically managed rotations and one conventional rotation were evaluated. Each organic crop rotation included potato as the main cash crop and at least one other cash crop in a 4-year rotation. Organically managed cash crops generated higher net revenues than the conventional potato system only if the average organic price premium was applied, because of lower yields and higher costs (Khakbazan *et al.*, 2015). A traditional potato–cereal–green manure rotation produced economic benefits similar to most of the organic rotations.

Costs and benefits to consider in an economic evaluation of rotations would include the fixed and variable costs of maintaining planting, cultivation and harvesting equipment for multiple crops, extra labour for moving livestock from paddock to paddock, fencing and possibly greater management costs due to complex planning, scheduling and marketing. In addition, if resistant crops are included in rotations or paddocks, then the costs and benefits of these must also be considered.

Because simple rotations, particularly those with just two crops, may select for rotation resistance in the pest, the dynamics of evolving resistance should also be considered in economic evaluations. Onstad *et al.* (2003) used a model that simulated the population dynamics and genetics of *Diabrotica virgifera virgifera* in a landscape of maize, soybean (*Glycine max*) and winter wheat (*Triticum aestivum*) where evolution of resistance to crop rotation may occur. Behavioural resistance has evolved in this major pest of maize in areas where 85–90% of farmers rotate maize to soybean and back to maize every 3 years (2-year schedule). Onstad *et al.* (2003) economically evaluated six alternative management strategies over a 15-year time horizon, as well as a strategy involving a 2-year rotation of maize and soybean in 85% of the landscape. Generally, resistance to crop rotation evolved in fewer than 15 years (15 pest generations), and the rate of evolution increases as the level of rotated landscape (selection pressure) increases. The two most successful strategies for delaying resistance were the use of transgenic insecticidal maize in a 2-year rotation and a 3-year rotation of maize, soybean and wheat with unattractive wheat (for oviposition) preceding maize. Economically, a 2-year rotation of soybean and transgenic insecticidal maize was a robust solution to the problem, if the technology fee charged for the host-plant resistance in maize was not too high (Onstad *et al.*, 2003).

Physical design of landscape

The physical landscape and structural components and configuration of farms can greatly influence

IPM. This is true for production of annual crops or perennial crops (orchards, vineyards, tree plantations) and livestock farms. When we evaluate the economics of public health programmes in cities, we should also consider the influence of landscapes. Note that the important landscape components could be terrestrial or aquatic depending on the pest and its natural enemies.

For conservation biological control usually involving the promotion of native natural enemies, public research and development efforts that should be included in economic analyses include extensive field testing of best practices in habitat alteration, alteration of productive resources for natural enemies and away from other uses, and any costly adjustments in other private agricultural practices or in public health plans. Ecological engineering is a new term being used to describe habitat manipulation and landscape design (Gurr *et al*., 2004).

Control based on decisions during a season

Augmentative biological control

With augmentative biological control, pathogens, parasitoids or predators are released into fields or farms every season or year. Industry, grower cooperatives or government agencies make the major investments up front that permit the annual production of natural enemies in a production facility (Tauber *et al*., 2000). These stakeholders need to understand the long-term returns on the investments. For the farmers or other users of the seasonal control, the investment in the production facilities can be seen as sunk costs that determine, to some extent, the cost of the purchased batch of biological control agents. Augmentative biological control requires annual rearing, storage and delivery of living organisms (McEwen *et al*., 1999). After delivery of biological control agents to a farm, costs are incurred to spread the natural enemies throughout the fields. Again, these organisms must be stored and handled carefully on the farm. Even when augmentative biological control applied seasonally is part of a predetermined schedule/design, the large quantity of biological control agents released in inundative efforts require significant annual costs, which are not usually part of classical biological control programmes.

Because the cost of rearing natural enemies is frequently taken for granted or forgotten in evaluations of augmentative biological control, we provide a short review of several papers that describe these costs. Vieira *et al*. (2017) determined the cost of rearing a parasitoid that attacks eggs of pests in the genus *Spodoptera*. They found that the cost of rearing the parasitoid on an alternate Lepidopteran host in the family Pyralidae was only $0.0002/parasitoid versus the $0.0004/parasitoid when reared on *Spodoptera frugiperda*. *Galleria mellonella* can be a serious pest of hives of *A. mellifera*, causing millions of dollars in damage to the honey industry in the 1980s in the United States (Dougherty *et al*., 1982). Dougherty *et al*. (1982) discovered that the nucleopolyhedrosis virus of this pest has similar virulence after production either *in vitro* or *in vivo*. They calculated that the cost of *in vitro* production was much less than a dollar per ten-frame hive. In a series of papers, Coudron and others demonstrated the feasibility of rearing predaceous stink bugs (Pentatomidae) on artificial, insect-free diets to produce effective biological control agents (Wittmeyer and Coudron, 2001; Coudron *et al*., 2002; Coudron and Kim, 2004). In comparison with the conventional rearing on *Trichoplusia ni*, a natural prey, they found that developmental times were prolonged and net reproductive rate was lower on an insect-free diet. However, the studies showed that the cost of rearing approached 1.1 times the cost of rearing on *T. ni*.

Insecticides and chemicals used to attract, confuse or repel pests

Chemical insecticides, both synthetic and derived from natural sources, are typically sold seasonally to farmers or public health officials who often use the products according to perceptions or measurements made during the season. The manufacturers of the chemicals invest in research, development and production. A recent estimate of the cost of developing one commercial insecticide is $286 million over an 11-year period (Sparks and Lorsbach, 2017). (For a view of biopesticides, see the overview provided by Bailey *et al*., 2010.) The insecticide users pay a price for each product partially based on the costs incurred by the corporations. Onstad *et al*. (Chapter 7) discuss much more about insecticides.

Semio-chemicals are pheromones and kairomones and other natural chemicals used to disrupt or trap the pest population. Clearly, pheromone trapping and mating disruption are tactics involving these chemicals. If these are applied on a schedule determined before the beginning of the season, then this approach could be considered part of the design or long-term management plan. However, when the extent of their use is based on seasonal knowledge, then farmers and other users may consider the economics to be similar to those for insecticidal control. The manufacturers of the chemicals invest in research, development and production.

Note that insects can evolve resistance to any of these chemicals over the long term (Onstad 2014). Thus, some economic analyses may account for declining benefits due to evolution.

Genetic control

Brown *et al*. (Chapter 6) describe economic analyses for genetic control. Genetic modification of a pest population involves extensive research and development requiring at least as much investment in facilities and rearing as augmentative biological control. The additional costs for genetic control certainly are due to the need to maintain colonies of different phenotypes not just one colony for the species. Greater oversight by government regulatory agencies and non-profit organizations likely increase costs even more compared with biological control. Again, economic analyses may need to account for declining benefits of genetic control as resistance evolves.

The Challenge and the Opportunity

We chose the title of this book carefully. The word 'integrated' was added not just because of the background to the term IPM and a minor necessity to match the acronym and title. We firmly believe that the theory and practice of IPM are critical to the future of our society. We also strongly believe that integration of tactics and redesigning systems without consideration of economics is foolish and counterproductive. Although some entomologists may believe that the practice of IPM has not come close to the ideals imagined in the 1960s and 1970s, new solutions have been developed. Even since Kogan's (1998) review, area-wide pest management (Koul *et al*., 2008) and insect resistance management (Onstad, 2014) have added new dimensions to IPM. Area-wide management emphasizes the advantages of larger spatial scales and coordinated, if not cooperative, efforts. Insect resistance management is essentially long-term, area-wide IPM (Onstad, 2014).

We have asked all authors to highlight three themes in their chapters. The first is the real and potential roles of design in pest management. If nothing else, this will prevent us from taking design for granted. The second theme is the value of taking a long-term perspective. As noted above, stakeholders may need our help viewing the costs and benefits over several decades after a decision is made. The third theme for the book is the consideration of the influence of human behaviour in IPM. We do not mean the standard transactional economic behaviour measured in the simplest analyses. We mean the extra behaviours considered by behavioural economists, and those that make our analyses more difficult. Do the customers and users of IPM behave in ways, individually or socially, to make IPM more difficult to implement in agriculture or public health? Should more research focus on this area? How can education contribute to better IPM? We will attempt to summarize any conclusions that can be drawn about these three themes in our concluding chapter.

Ten years ago, Onstad and Knolhoff (2009) collected data to determine how frequently economic evaluations of insect IPM occur. They used CAB Abstracts, a bibliographic database, to survey entomological journals representing the discipline of economic entomology: *Journal of Economic Entomology* (*JEE*), *Journal of Medical Entomology*, *Bulletin of Entomological Research* and *Journal of Applied Entomology*. Half of the articles surveyed were published by *JEE*. Onstad and Knolhoff (2009) found that less than 1% of research papers published between 1972 and 2006 (almost 2% in *JEE*) included economic evaluations of pest management tactics. At least 85% of these analyses were performed by entomologists, not economists. Onstad and Knolhoff (2009) concluded that economic entomologists may need to take steps to enhance the research that supports these evaluations, if they ultimately want to determine the value of different kinds of tactics for farmers and society.

To determine if activity had changed since 2007, we performed a similar survey of the journals *Crop Protection* and *JEE* for the period 2010–2015 using Scopus, another bibliographic database. *JEE* published 1744 articles during this period and we obtained 145 hits on the term 'economic' in our search. Of these, only 18 articles reported on an economic evaluation; 6 out of the 18 had an economist as an author. For *Crop Protection*, 1601 articles were published. We obtained 139 hits with

~40% being entomological in this multi-disciplinary journal. Only 9 articles during 2010–2015 had economic analyses of insect problems; 2 of 9 had an economist as an author. The percentage <1% of articles reporting economic analyses matched the results of Onstad and Knolhoff (2009). The proportion in *JEE* declined slightly from a long-term 2% to 1%. Before 2008, at least 85% of these analyses were performed by entomologists, not economists; after 2010, the percentage declined to 67%.

Rejesus (Chapter 3) and Norton *et al*. (Chapter 8) present many examples of IPM programmes around the world. The complex economic analyses reviewed in these two chapters provide insight into what has worked and what difficulties must still be overcome. Economic journals do publish most of these more sophisticated methods, but, as Norton and Mullen (1994) noted, these journals should not be expected to contain or represent most of the empirical studies that use established methods. Thus, entomologists and others interested in surveying the conclusions drawn from empirical economic studies must explore non-economic journals, documents and sites on the internet to complete their work.

Arthur (2010) stated that the top research need for stored product entomology is the integration of economic analyses into applied management programmes for insect pests. These pests impact the viability of a wide range of businesses including farms, flour mills, food warehouses, distribution centres and retail stores. Arthur (2010) hoped that economic analyses could improve decision making tools and provide cost–benefit evaluations for individual facilities. We support Arthur (2010) and hope that economic analyses can become more common because they are critical to IPM and entomology (Mitchell and Hutchison, 2009).

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2

Economic Evaluation of Integrated Mosquito Control in Urban Areas

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Traditional vector control programmes are facing complex challenges due to the multitude of invasive vectors and arboviruses. These challenges call for new techniques that target multiple mosquito species (Little, 2017), one of which is area-wide pest management (AWPM). In this chapter, we will focus on the economic impact of AWPM to mitigate and control *Aedes albopictus*, also known as the Asian tiger mosquito, a vector that carries a number of mosquito-borne diseases and is a source of nuisance.

This chapter first answers general economic questions such as: What is an economic evaluation? Why do we need an economic evaluation? Second, we present the recommended framework for one type of economic evaluation. Third, we illustrate the framework using a case study based on our economic evaluation of AWPM to control *Ae. albopictus* in urban areas in Mercer and Monmouth Counties in New Jersey, USA. Finally, we conclude with summary observations and implications about our application of the economic evaluation framework to the mosquito control efforts in these urban areas of New Jersey, and the usefulness of the evaluation in that application.

What is Economic Evaluation?

Economics is the science of studying human behaviour concerning the interaction between needs and limited resources that have alternative uses (Robbins, 1935). This field of science aims to maximize human welfare or utility by methodologically analysing situations where human beings have to make choices from limited options. Rising cost, often associated with the introduction of new technologies, and spending limits have prompted the search for greater efficiency. From an economist's perspective, rational management decisions should be based on an efficiency analysis to explore the best use of limited resources, and informed assessment of the costs and benefits of prospective programmes or interventions. Economic evaluation, also known as efficiency evaluation, is a comparative analysis of alternative courses of action in terms of both their costs and consequences (Drummond *et al.*, 2005; Botchkarev, 2016).

Why Do We Need an Economic Evaluation?

In the United States and other free market-oriented countries, the production and distribution of goods lies in the private sector rather than the public sector. This private-oriented form of economic organization is believed to lead to an efficient allocation of resources. However, under certain circumstances the free market model does not work as efficiently as expected. There are some goods that either will not be supplied by the market, or supplied in insufficient quantity. Under these circumstances, government intervention is required to offset the market failure.

Public goods are one example of market failure. Public goods do not cost more for an additional individual to enjoy their benefits, and it is difficult to exclude individuals from enjoying the benefits of these public goods. When there is no marginal cost

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for an additional individual to use a good or service, it should not be rationed. However, if this good or service is to be privately provided, the private sector would charge for its use. Charges for the use of a public good will discourage individuals from using it, resulting in underutilization of these goods and services. Underutilization, in turn, might lead to another market failure, i.e. externalities. Externalities occur when the action of one individual or firm affects other individuals and firms by imposing some kind of cost on others, but does not compensate them for that cost.

In the public sector, decisions made about various policies, programmes or services have consequences for society as a whole. The supply of public goods is determined through a policy process led by elected representatives who need to allocate the government budget among competing programmes based on voters' interests and preferences. The allocation of resources among public programmes is determined by the need for the public programme, the market failures the programme addresses and the form of government intervention initiated to address the market failure. More information on this topic is presented by Stiglitz (1988).

Management of mosquitoes and other disease vectors is a public good: if applied successfully, it reduces and controls pests and produces a benefit that protects the whole community. In this sense, it is a public service that must be provided collectively to all residents. Underutilization of this service would lead to costly negative externalities such as the increasing threat of vector-borne diseases, including dengue and yellow fever, and reducing residents' outdoors activities due to nuisance from pests, to name a few.

Public goods and externalities justify government intervention to address market failures. The decision to invest in an intervention to address market failure must be determined by three dimensions: the intervention's efficacy, effectiveness and availability (Drummond *et al.*, 2005). When these dimensions are met, economic evaluation is then used to quantify the efficiencies of this intervention relative to other options, including the status quo (Boardman *et al.*, 2006). There are three types of efficiencies to be considered: technical efficiency, productive efficiency and allocation efficiency. Technical efficiency addresses the issue of using a set of resources to maximum outcome; productive efficiency addresses the issue of choosing different combinations of resources to achieve the maximum benefit for a given cost; and allocation efficiency addresses the issue of achieving the right mixture of services or goods to maximize the health and welfare of society (Slothuus, 2000). In economic evaluation, we are mostly interested in the allocation efficiency.

Framework for an Economic Evaluation

There are four general phases to conducting an economic evaluation: establish the research question; plan the study design; identify, measure, and value the cost and outcomes; and calculate the incremental costs and outcomes of the alternatives being considered in the economic evaluation.

Phase 1 Research question

Defining the research question is very important and needs a lot of consideration. This step should include a clear definition of the problem, explain why it is important, and describe which aspect of the problem would be addressed by the intervention and how. During this phase of the study we need to clearly define the reference case, i.e. the alternative scenario, and specify whose perspective we plan to use. The government perspective is a limited perspective, such as a county or state vector control programme. A more inclusive perspective considers all of society (i.e. local, state and federal vector control programmes, as well as residents' perspective). The perspective used in an economic evaluation can have an influence on which costs are included in the evaluation and which outcome measures would be considered in the analysis. For example, if the study applies only to a public sector, the study is said to assume a public sector's perspective (i.e. a limited perspective) and will focus on costs incurred by, and outcome measures relevant to, the public sector. However, when the study applies to the society as a whole, it is said to assume a societal perspective. The costs and outcomes in the societal perspective refer to cost and outcomes sustained by everyone who might be affected by the intervention. In both perspectives, the geographical boundaries of the analysis need to be explicit, such as specified counties, a state or a country (Drummond *et al.*, 2005; Muennig, 2008).

We should also clearly describe the nature of the intervention, the target population, intervention site(s), personnel, the technology we plan to use, the time frame of the study and analytical horizon.

This information would help determine whether the study period is long enough to account for programme start-up costs, maintenance costs and seasonal variations, and to capture the full costs and outcomes, both intended and unintended, of the intervention. This step should also indicate and describe the competing alternatives, including the status quo (Task Force on Community Preventive Services, 2005).

Phase 2 Study design

In the second phase we plan the study design. Ideally, economic evaluation would be designed as a component of a randomized control trial, e.g. Area-wide management of the *Ae. albopictus* in Mercer and Monmouth Counties in New Jersey. This allows for accurate data collection of cost and outcomes. However, a randomized control trial may be limited in time, measurement (i.e. intermediate outcomes) and comparison options. These limitations prompt researchers to include simulation modelling as an extension of their trial to allow synthesis of evidence and outcomes, or as a standalone modelling study using cost and outcome indicators from existing literature (Shafie *et al.*, 2017). It is highly recommended that economists be involved in the early stages of study design, as the design of the costing study can greatly impact the cost estimates (Raftery, 2000).

Phase 3 Identify, measure, value costs and outcomes

In the third phase we identify, measure and value both costs and outcomes (Raftery, 2000). As mentioned above, the study perspective will influence which cost and outcome measures would be included in the economic evaluation. From the societal perspective, all costs must be included, regardless of who pays for them. For example, a societal perspective of an AWPM study in New Jersey includes public agencies as well as household expenditure on pest management. In contrast, a public perspective focuses only on the cost to public agencies, including local pest management programmes.

Identify, measure and value costs

The cost includes all inputs involved in the development and implementation of the intervention. The cost can be measured as total cost, marginal cost, average cost and incremental cost. Total cost is the total amount paid for input that arises as a consequence of implementing the intervention. Marginal cost is the change in costs for a given change in output. Average cost is the cost per unit of output. Incremental cost is the change in the total cost associated with some change in output quantity. For the purpose of the economic evaluation, the marginal cost is the key measure, since the principal of cost in economic evaluation is the cost that arises from the production of one extra unit, not the average cost *per se* (Slothuus, 2000).

Cost can be direct or indirect. Direct cost comprises the cost of all resources consumed for the programme. Indirect cost comprises the cost of resources that occur indirectly due to the programme. One type of cost that we should not count is sunk or historical cost. Sunk costs are costs that are unavoidable, usually because they were already incurred. Once incurred, they should play no role in any subsequent decision. For the purpose of economic evaluation, only the avoidable costs are relevant. These avoidable costs can be fixed or variable costs. Fixed cost is a constant cost that does not change in the short term, regardless of the quantity of goods or services provided, e.g. the annual rent paid for a storage facility. Variable costs are costs of inputs that might change because of the intervention, such as fumigation or informational flyers.

We usually start by developing a cost inventory that identifies and lists, as comprehensively as possible, the resources used in implementing the intervention. The norm is to include all consumed resources that are large enough to have an impact on decision making (Drummond *et al.*, 2005). After identifying the resources, we should categorize and measure, in appropriate physical units, all important and relevant costs and consequences of both intervention and potential alternative(s), including the status quo.

To identify and categorize resources, we should consider the level of responsibility (federal, state, local), and the source of funding (public or private). We usually begin the costing activity using the line item expenditure data, which covers three key categories: personnel, recurrent and capital costs. The personnel cost covers the salaries of full- and part-time employees, the wages of seasonal staff and value of volunteers. Fringe benefits, such as health insurance and paid vacation and sick days, received by personnel as part of their employment benefits should be included even if these benefits are not paid directly by the agency implementing the intervention. To capture the full cost of personnel we need to include the in-kind costs, such as unpaid work or volunteer work. The norm is to use the market value of services similar to those provided in-kind to quantify the cost of in-kind contributions.

Recurrent costs capture all non-personnel cost consumed within a period of 1 year. These costs include materials and supplies, operating costs, insurance, maintenance, consultancy fees, travel, incentives, workshops, special annual licences, fumigation materials, etc. Capital costs are all non-personnel costs with a lifetime use exceeding 1 year, such as buildings, equipment, and may include software, if the lifetime of that software exceeds 1 year. Since capital costs represent items with a useful life exceeding 1 year, their cost must be allocated over the lifetime during which they are expected to be used. To perform this step, we amortize the capital cost using three variables: the replacement cost of the item, its expected lifetime (in years) and an interest rate, usually 3% per year. Most capital costs are fixed costs, since they do not vary with output. Costing activities in the economic evaluation consider not only the financial cost of all resources, but also the true cost of these resources. If no cost information is currently available for an item, or if the available cost does not reflect the societal value of resources, then the true cost of these resources must be imputed, e.g. shadow or proxy pricing (Raftery, 2000; Belli *et al*., 2001). For donated items, replacement cost using current market prices for similar items are used as a proxy for their cost (Shepard *et al*., 2000). In some cases the intervention might lead to unintended consequences, both favourable and unfavourable. These unintended consequences should be valued and included in the computation of the net cost.

Strategies in measuring costs

Two strategies are used in measuring and assessing cost: the micro-costing approach, also known as the line item or ingredients cost method, and the macro-costing approach, also known as the top-down approach. Micro-costing refers to detailed analysis of the cost of the resource use due to a particular intervention, using tools such as time and motion studies. To conduct micro-costing, we would start by identifying all the relevant resources that will be consumed, quantify the resources used and place a monetary value on the resources. Such detailed, bottom-up collection of data on resource use may be necessary when changes are being made to existing services. In most cases, we would need to develop and use a customized tool to capture the cost and impute the cost of some items, as discussed above. While micro-costing is the most favourable method to estimate the cost due to the level of detailed and comprehensive data it generates, the effort it requires tends to make it costly and it runs the risk of being specific to particular contexts (Raftery, 2000).

In the macro-costing approach we allocate the total budget to specific services. The simplicity of top-down costing may be offset by a lack of sensitivity, which in turn depends on the type of routine data available (Raftery, 2000). The decision on which approach to use, in most cases, depends on the needs of the analysis. Many studies apply a mixture of the two, using micro-costing for the direct costs associated with the intervention, and macro-costing for indirect costs. For example, costs incurred long after the intervention, when discounted, will be greatly reduced in value. For this type of cost, a macro-costing approach is recommended (Raftery, 2000). As the choice of the costing approach can impact the cost estimates, adjustment based on an estimation approach should be incorporated into sensitivity analyses (Olsson, 2011). In all cases, we should clearly state the sources and methods used to value both the costs and outcomes. Costs are usually valued in units of local currency based on prevailing prices of personnel, commodities and services and can be taken directly from the programme's budgets. All current and future costs should be valued in constant dollars of the base year to adjust for inflation (Drummond *et al*., 2005). Future cost should be converted to present value using the present value formula $PV = FV[1/(1 + R)^\wedge N]$, where PV stands for present value, FV stands for future value or cost, R is the discount rate and N is period of time.

Strategies in valuing outcomes

When we value outcomes, it is important to clearly state whose preferences we are considering, the general population or a targeted group, and discount future benefits and outcomes to present values (Drummond *et al*., 2005). A number of tools have been developed to measure the benefit of an intervention using a monetary measure of utility.

These techniques measure both revealed preferences (actual markets) and stated preferences (hypothetical markets). Measuring stated preferences is an alternative method used when it is not possible to obtain direct answers or observe economic actions. These methods determine individuals' preferences by asking hypothetical questions about how much individuals would be willing to pay (WTP) or willing to accept for a change from the status quo. These techniques measure benefits, especially in situations where there is a need to elicit the value of a public good or of non-marketed resources.

One method for valuing a non-market resource is the contingent valuation, a survey-based approach for valuing non-market goods (Mitchell and Carson, 1998; Carson and Hanneeman, 2005; Freeman *et al.*, 2014). There are three elicitation approaches to ask contingent valuation questions. In an open-ended approach, the respondent is asked to mention the amount they would be willing to pay for a certain service. With the closed-ended approach, the respondent is asked whether they would be willing to pay a specific amount. In the bids approach, respondents are given a dichotomous choice of yes and no and are first asked whether they would be willing to pay a specific amount; then the question is repeated using a higher or lower bid value depending on the response to the first question (Mitchell and Carson, 1998).

Another approach, the conjoint analysis, is based on the information integration theory developed by Anderson and conceptualized by Louviere (Anderson, 1970, 1981, 1982; Louviere, 1988). Similar to contingent valuation, it is used in economic evaluation to value non-marketed commodities (Ryan and Gerard, 2003), and to simulate the decision processes in the real world. By using conjoint methods, the complete programme or service is evaluated, allowing respondents to incorporate the same trade-off processes they use in actual decision making (Yeh, 1998).

In conjoint or trade-off analysis, profiles or scenarios describe the programme or service of interest. Each scenario is a combination of one arbitrarily selected level for each of the attributes. Attributes are the key features of the programme, policy or service evaluated, while levels are those specific points evaluated for the key features (Louviere, 1988). The two key objectives of conjoint analysis are first to evaluate the contributions of the attributes' features and the values of their separate levels on the determination of an individual's preferences, and second to build a valid model of individuals' judgements that is useful for predicting the acceptance of any combination of attributes, even those not evaluated by the sampled population. The conjoint analysis uses several techniques including traditional conjoint analysis, maximum different scaling, choice-based conjoint analysis and adaptive choice-based conjoint analysis (Orme, 2010; Rao, 2014).

Past empirical studies

Few empirical studies have been conducted to economically evaluate mosquito control. Von Hirsch and Becker highlighted the low tolerance the public has for mosquitoes in the Upper Rhine Valley, Germany, where a small number of mosquitoes were enough to cause nuisance. Using contingent valuation, the study's authors estimated the median WTP for mosquito control using the biological control agent *Bacillus thuringiensis* serotype israelensis (BTI) at US$5.42 per person per year compared with the cost of $1.42 per person per year (Von Hirsch and Becker, 2009). Halasa *et al.* (2012) used contingent valuation to estimate the perceived value of an AWPM to mitigate *Ae. albopictus* in New Jersey, USA (Halasa *et al.*, 2012). The mean WTP for an enhanced mosquito abatement programme was estimated at $11.31 per person per year. To estimate the public benefits of reducing the risk of *Ae. albopictus* invasion on the Australian mainland, Mwebaze *et al.* used contingent valuation to elicit the public's preferences for a programme that has the potential to mitigate the threat of *Ae. albopictus* establishment in Australia (Mwebaze *et al.*, 2017). They found people were willing to pay $29.26 per person for a programme that mitigates the high threat of *Ae. albopictus* to a lower threat, and $21.78 per person for a programme that reduces the threat of *Ae. albopictus* from high to moderate (Mwebaze *et al.*, 2017).

Dickinson and Paskewitz used a choice experiment design to estimate the average WTP an additional property tax for a pest management programme that reduces Madison, Wisconsin residents' exposure to pest insects to control the risk of West Nile virus transmission and reduce nuisance mosquitoes (Dickinson and Paskewitz, 2012). Interestingly, those who responded to the survey were not willing to pay for a programme that targeted West Nile-transmitting mosquitoes only, but willing to pay $57.19 per person per year for a programme that reduced nuisance mosquitoes, and $83.67 per person per year to reduce the high risk of transmitting mosquito-borne diseases (Dickinson and Paskewitz, 2012). Akter *et al.* conducted a choice experiment study to elicit the non-market value of biosecurity generated from portfolio analysis to non-market goods. Respondents were willing to pay $104.85 to reduce biting pests in backyards and outdoor areas from medium chance (30–50%) to low chance (10–30%), and $204.36 from high chance (50–70%) to medium chance (Akter *et al.*, 2015).

When we value outcomes, it is important to clearly state whose preferences we are considering, the general population or a targeted group, and discount future benefits and outcomes to present values (Drummond *et al.*, 2005). The outcomes of the intervention can be measured in various ways depending on the selected measures. If the outcome measure is in monetary value, then we can measure the monetary value of the utility gained or lost using indirect methods such as WTP that determine individuals' hidden preferences (Boardman *et al.*, 2006). If the outcome is measured in natural units, such as additional hours of yard activities saved, this one-dimensional effect would be sufficient to conduct a cost-effectiveness analysis. We can also measure the outcome as a utility using a scale instrument or existing special multi-dimensional measures such as quality adjusted life years.

It is important to keep in mind that programmes might lead to unintended consequences. The cost associated with these unintended consequences should be included in the cost analysis and measured as part of the outcomes. For example, initial vector control efforts through the use of single insecticides to control malaria have led to the development of mosquito resistance against those products.

Phase 4 Calculate the incremental costs and outcomes

In the fourth step, we compare the incremental costs and outcomes of the alternatives being considered by estimating the additional cost and additional benefits of one intervention compared with another, or compared with the status quo. This calculates the additional cost incurred for added activities proposed by the new intervention (Drummond *et al.*, 2005).

Case Study: AWPM in New Jersey

Vector control is an important public service. With the spread and establishment of *Ae. albopictus* in new localities, concerns over the potential public health threat of this mosquito vector and its impact on residents' daily activities call for new ways of managing this pest, since standard mosquito abatement approaches achieve limited impact in controlling this species (Farajollahi and Nelder, 2009). We partnered with Rutgers University in New Jersey and officials from Mercer and Monmouth Counties to conduct an economic evaluation of the AWPM programme for control of *Ae. albopictus* in their counties (Halasa *et al.*, 2012, 2014; Shepard *et al.*, 2014). The AWPM involved multiple components: public education, reduction in breeding sites, monitoring, fogging and occasional use of insecticides (pyroproxifen). It thus illustrates an integrated vector management programme.

Cost of AWPM

To estimate the cost, we started by specifying the study perspective, reference case and study period. Our study used the Mercer and Monmouth Counties' perspectives, used the traditional vector control as a reference case, and calculated the cost of both the traditional vector control activities and the AWPM activities in both the intervention areas (Cliffwood Beach in Monmouth County and South Olden in Mercer County) and control areas (Union Beach in Monmouth County and Cummings in Mercer County) for the years 2007 through 2011. The study period covers 2 years prior to the AWPM programme and 3 years of AWPM programme.

We began by identifying the key activities of the AWPM programme and traditional mosquito control. The passive traditional mosquito control activities include source reduction (i.e. removal of water sources that serve as larval sites), treating larvae and/or adults with insecticides, and resident education as a component of residents' routine service requests. The area-wide approach includes five major components: assessment, operations/implementation, research, education and reassessment. In addition, it involves coordinating activities over a large area to reduce the overall densities of insect pests, and minimizing the risk of initial infestation and re-infestation after pests have been controlled (Flinn *et al.*, 2003). The AWPM activities include operational surveillance and vector control activities such as treating larvae and/or adults with insecticides, mosquito-source reduction, and an educational component.

During implementation, officials from Mercer and Monmouth Counties added the AWPM activities to their routine vector control activities. We developed a costing tool to list and capture resources used for vector control. These resources fell into four key categories: personnel, recurrent costs, capital purchases and capital costs. We then measured the resources used based on official documents and interviews with county officials, and valued these resources based on financial records. For donated and some capital items, the costs were estimated using the market values (i.e. how much it would cost if these items were to be purchased today). We amortized capital items based on their useful lives according to Internal Revenue Service instructions for property and equipment accounting (Internal Revenue Service, 2016) and used the discount rate of 3% per year. Interviews with county officials assisted in distributing resources between activities allocated to controlling *Ae. albopictus* and other pests, and in allocating *Ae. albopictus* activities between traditional control activities and the AWPM project.

After identifying activities, resources and the costs allocated to the AWPM activities, we assigned the costs to the AWPM functions, i.e. treating larvae and/or adults with insecticides, source reduction, surveillance, education and research. Figure 2.1 illustrates the cost of *Ae. albopictus* control activities in the AWPM intervention areas by function. Table 2.1 shows the cost of vector control activities to control *Ae. albopictus* (using a combination of AWPM and traditional vector control approaches) in the intervention areas, compared with the traditional approach alone in the control areas. The average incremental cost for the years 2009–2011 was $37.19 per capita, in 2018 US$.

The impact of AWPM

To study the impact of the AWPM, we considered the health risk and the nuisance associated with this day-biting mosquito and its impact on residents' daily activities. However, for the purpose of our study, we focused on the main direct and immediate impact of the AWPM project, which allowed residents to use and enjoy their yard and porch activities without the nuisance of mosquitoes. Therefore, we selected three measures for this

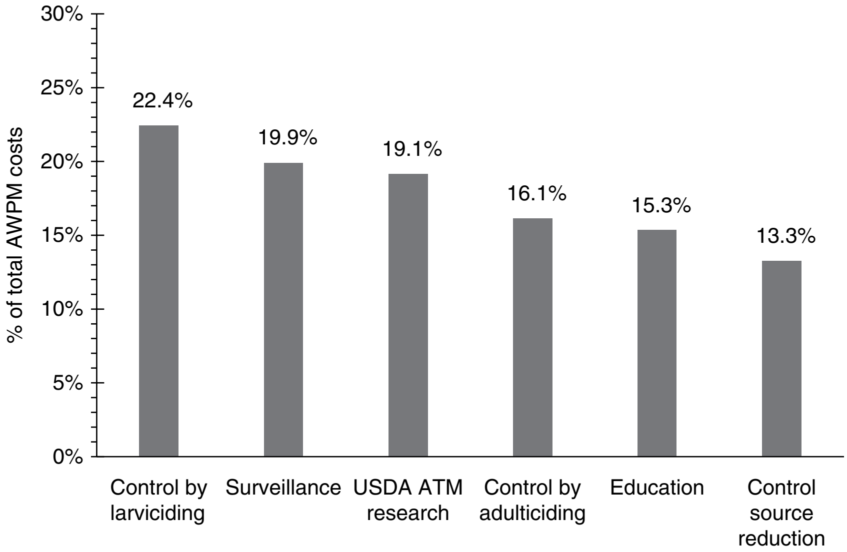

Fig. 2.1. Percentage of AWPM costs for each component 2009–2011 (overall average of $40 per capita), in 2018 US$. The education component includes the cost to Rutgers University of developing and distributing educational materials. AWPM denotes area-wide pest management; USDA denotes United States Department of Agriculture; ATM denotes Asian tiger mosquito.

Table 2.1. The per capita cost of *Ae. albopictus* control activities in the intervention and control areas of the Mercer and Monmouth Counties, NJ, and the per capita incremental cost of area-wide pest management (AWPM) from 2009 to 2011, in 2018 US$.

	2007	2008	2009	2010	2011	Average (2009–2011)
Per capita cost of controlling *Ae. albopictus* in intervention areas ($)	1.26	1.48	44.86	49.30	25.87	40.01
Per capita cost of controlling *Ae. albopictus* in control areas ($)	0.79	0.93	0.87	0.39	7.20	2.82
Per capita incremental cost of AWPM ($)	0.47	0.55	43.99	48.92	18.66	37.19

evaluation. First, the reduction in the average number of hours of yard and porch activities lost because of mosquitoes during a typical summer week, such as eating and cooking in the yard or on the porch, gardening, relaxing and socializing, playing and maintaining house or car (a measure used for the cost-effectiveness analysis). Second, we estimated the maximum amount residents would be willing to pay for a programme that would reduce mosquito abundance by estimating residents' perceived value of an additional hour an adult resident could spend enjoying yard and porch activities free of mosquitoes during a typical summer week (a measure used for the benefit–cost analysis). Third, we measured the improvement in residents' utility, or satisfaction associated with the AWPM (a measure used for the cost–utility analysis).

Hours lost due to mosquitoes in urban areas

To estimate the reduction in the average number of hours lost engaged in yard and porch activities during a typical summer week, we sent annual mailed surveys for a randomly selected sample of residents in the intervention and control areas. These surveys were conducted from 2008 (prior to the intervention) through 2011 (3 years of intervention). The sample sizes ranged from 310 in 2008 to 548 in 2011. The surveys allowed us to measure the effectiveness of the AWPM project in reducing the number of hours lost per yard and porch activity due to mosquitoes. The two key survey questions, Questionnaire 1 and Questionnaire 2, are presented below. The difference between responses from Questionnaire 2 and Questionnaire 1 captures the hours lost due to mosquito nuisance.

Questionnaire 1. During a typical summer week, how many hours per week did you and/or your selected child spend on your outdoor porch, steps or yard engaged in each of the following activities? (If none, put 0.)

Activity in outdoor porch or yard	Hours you spent in typical week	Hours selected child spent in typical week
a. Eating or cook out		
b. Gardening or mowing lawn		
c. Maintaining house or car		
d. Playing catch, frisbee, bocce, horseshoes, croquet, volleyball/badminton, etc.		
e. Relaxing, socializing, talking, reading, hanging out, smoking		
f. Others – please specify below		

Questionnaire 2. We are interested in the impact of mosquitoes on outdoors porch or yard activities. During a typical summer week, how many hours per week would you and/or your selected child have spent on your outdoor porch or yard if you and/or your selected child had no concerns over mosquitoes?

Activity in outdoor porch or yard	Hours you would have spent in a typical summer week	Hours selected child would have spent in a typical summer week
a. Eating or cook out		
b. Gardening or mowing lawn		
c. Maintaining house or car		
d. Playing catch, frisbee, bocce, horseshoes, croquet, volleyball/badminton, etc.		
e. Relaxing, socializing, talking, reading, hanging out, smoking		
f. Others – please specify below		

Table 2.2. Difference-in-differences in the number of hours of yard and porch activities lost due to mosquitoes in Mercer and Monmouth Counties, NJ from 2008 through 2011.

	Eating	Gardening	Maintaining home/yard/car	Playing	Relaxing	Total hours
Year 2008						
AWPM						
Mean	2.78	1.45	0.65	1.06	3.62	9.09
SEM	0.36	0.22	0.14	0.19	0.45	1.01
Control						
Mean	2.03	1.11	0.45	0.89	2.54	6.50
SEM	0.27	0.19	0.11	0.18	0.33	0.83
Average 2009–2011						
AWPM						
Mean	4.26	2.48	1.85	3.12	5.60	16.85
SEM	0.25	0.18	0.13	0.18	0.35	0.88
Control						
Mean	4.60	3.06	2.30	3.35	5.77	18.71
SEM	0.25	0.19	0.14	0.17	0.33	0.88
Difference-in-differences+						
Mean	–1.09	–0.91	–0.65	–0.41	–1.25	–4.45
SEM	0.57	0.39	0.26	0.36	0.74	1.80
	*	**	**	NS	*	**

AWPM denotes area-wide pest management; SEM denotes standard error of the mean; NS denotes not statistically significant; *denotes $p < 0.05$, **denotes $p < 0.01$, negative values denote favourable outcomes.

The AWPM started in 2009 and concluded in 2011. During the last year of the study, a new control strategy was introduced in Monmouth County. To control for potential lingering effect of previous treatment strategies, treatment and control sites were switched. To address the challenge associated with this new strategy, we used a crossover analysis to estimate the impact of AWPM on hours of yard and porch activities lost due to mosquitoes. We pooled the four surveys in one dataset to increase statistical power. We tested for any differences in the baseline populations between the pre- and post-intervention years using Chow tests (Chow, 1960). To address clustering due to some residents participating in more than one survey, we used a difference-in-differences analysis (Table 2.2) and a pooled ordinary least squares regression with cluster-robust standard errors (Table 2.3).

Table 2.3. Pooled ordinary least squares regression with cluster-robust standard error of the hours of yard and porch activities lost due to mosquitoes from 2008 through 2011 in Mercer and Monmouth Counties, NJ.

Independent variables	Eating		Gardening		Maintaining home/yard/car		Playing		Relaxing		Total hours		Reference category
Study years													
Year 2009	3.22	***	2.85	***	2.59	***	3.66	***	4.86	***	17.17	***	Year 2008
	(6.95)		(8.05)		(10.50)		(11.55)		(7.50)		(10.63)		
Year 2010	0.07		0.22		0.41	**	0.02		–0.03		0.76		
	(0.22)		(1.06)		(2.82)		(0.10)		(0.07)		(0.78)		
Year 2011	3.49	***	2.68	***	2.42	***	3.40	***	4.01	***	16.13	***	
	(8.15)		(8.56)		(11.22)		(12.14)		(7.13)		(11.34)		
Assigned intervention areas	–0.42		–0.94	**	–0.68	**	–0.35		–0.82		–3.30	*	Assigned control areas
	(1.03)		(3.06)		(3.11)		(1.25)		(1.44)		(2.35)		
Study areas													
AWPM, cluster 1 baseline	0.17		0.65		0.50	+	0.00		0.95		2.28		Mercer control area
	(0.30)		(1.55)		(1.82)		(0.01)		(1.26)		(1.21)		
AWPM, cluster 2 baseline	–0.03		0.50		0.21		0.36		0.88		1.96		
	(0.06)		(1.51)		(0.89)		(1.16)		(1.44)		(1.26)		
Control baseline	–0.40		0.21		0.23		0.07		0.25		0.40		
	(0.93)		(0.71)		(1.05)		(0.23)		(0.45)		(0.29)		
Attainment of a bachelor's degree or higher	–0.96	**	–0.62	*	–0.01		–0.64	*	–0.98	*	–3.18	**	Less than bachelor's degree
	(2.82)		(2.40)		(0.04)		(2.53)		(2.08)		(2.74)		
Constant	2.49	***	1.00	***	0.31	*	0.94	***	2.64	***	6.91	***	
	(7.00)		(4.21)		(1.98)		(4.12)		(5.99)		(6.30)		
Effectiveness of AWPM	0.42		0.94		0.68		0.35		0.82		3.30		
Hours lost in 2008	2.78		1.45		0.65		1.06		3.62		9.09		
% gained due to AWPM	15.0%		64.6%		104.5%		33.1%		22.7%		36.4%		
Observations	1581		1581		1581		1581		1581		1581		
R-squared	7.67%		8.35%		11.54%		16.66%		7.19%		13.88%		

AWPM denotes area-wide pest management; *t*-value in parentheses (ignoring sign); + denotes $p < 0.10$, *denotes $p < 0.05$, **denotes $p < 0.01$, ***denotes $p < 0.001$; the regression also included interaction terms between the areas and years, measuring the impact of the intervention being phased in starting in 2009 (coefficients not shown here).

In 2008, the baseline year, controlling for other factors, there was no statistical difference in the average number of hours adult residents spent in yard and porch activities during a typical summer week between the intervention (9.01 h) and control areas (6.5 h). The results confirm the comparability of these areas. After the implementation of AWPM, the average hours lost in 2009 through 2011 were 16.9 h in the AWPM areas, compared with 18.7 h in the control areas. The difference-in-differences analysis showed that the AWPM programme recouped 4.5 yard and porch hours per week previously lost by adult residents (Table 2.2). The ordinary least squares regression with cluster-robust standard errors indicates the AWPM project had a statistically significant impact and reduced the average total hours of yard and porch activities lost on typical summer week by 3.3 hours per week compared with control areas (Table 2.3). Our difference-in-differences and crossover analyses show the AWPM project had no significant impact on the hours a child spent engaged in yard and porch activities.

The utility associated with AWPM

We were the first, to our knowledge, to quantify residents' utility, or satisfaction, lost due to mosquitoes. Utilities are multi-dimensional measures used to calculate the quality adjusted life years gained from an intervention. This standardized unit allows for comparison among different programmes. The utility score lies between two values: 1 denoting perfect health, and 0 denoting deteriorated health status similar or equal to death. Therefore, higher utility score signals higher utility or satisfaction.

We used three methods to estimate residents' utility. The first was a disease states trade-off that compares experiencing an average day with mosquitoes, as they were in the summer of 2010 in the respondent's yard and porch, with selected health states. The second was the EuroQol state trade-off based on five diseases with mild disability weights derived from the Global Burden of Disease studies (Salomon *et al*., 2012). The third is the visual analogue scale.

The first approach, disease states trade-off, builds on the time-trade-off approach. Time trade-off is used in health economics to determine the quality of life of a patient or population. This approach instructs individuals to choose between living a fixed number of years (usually 10 years; denoted as F) in a specified health condition, and living Z years in perfect health. The difference Y ($Y = F - Z$) denotes the number of years the respondent is willing to trade to move from living in a specified health condition to living in perfect health. The number of years of perfect health selected (Z) is then converted into a utility score (generally Z/F) and used to calculate quality adjusted life years (Dolan *et al*., 1996). We modified the time-trade-off method to derive the mosquito abundance utility score by allowing residents to elicit preferences between alternative health states, instead of time, and living an average day with mosquitoes. This score measured how bothered residents were by the presence of mosquitoes, so that less abundant mosquitoes meant higher utilities. We asked respondents to remember how it was living an average day with mosquitoes as they were in their yard and porch that summer. We then asked them to select which, in their opinion, is a worse state: living an average day with mosquitoes as they were in their yard and porch that summer, or living in each of five health states selected, as presented in Questionnaire 3.

Questionnaire 3. Now I want you to think of the following conditions and choose the worst option.

1	a	Living an average day with influenza	b	Living an average day with mosquitoes as they are now in your yard and porch
2	a	Living an average day with a stomach flu (severe diarrhoea and vomiting)	b	Living an average day with mosquitoes as they are now in your yard and porch
3	a	Living an average day with severe hearing loss	b	Living an average day with mosquitoes as they are now in your yard and porch
4	a	Living an average day with a wrist fracture	b	Living an average day with mosquitoes as they are now in your yard and porch
5	a	Living an average day with a bronchitis	b	Living an average day with mosquitoes as they are now in your yard and porch

For the second approach, EuroQol state trade-off, we conceptualized five health states as steps on a ladder, so the respondent could indicate their mosquito acceptability score. These five health states were derived from the EuroQol EQ-5D descriptive system, which comprises health dimensions of mobility, self-care, usual activities, pain/discomfort and anxiety or depression. Each dimension has three levels: no problems, some problems and extreme problems, as presented in Questionnaire 4. These dimensions were analysed to generate a utility score that ranges between 1 (denoting perfect health) and 0 (equal to death). The five selected health states had utility scores ranging from 0.897 to 0.806 – the range that we expected would apply to most respondents (EuroQol, 2012).

Questionnaire 4. Now I want you to think of the current level of mosquitoes around your house and compare it with the following states and choose which is worse.

1	a	Living an average day with some problems with performing your usual activities (i.e. work, study, housework, family or leisure activities), but no problems in walking about, no problem with self-care, no pain or discomfort, and not anxious or depressed (11211)	b	Living an average day with mosquitoes as they are now in your yard and porch
2	a	Living an average day with some problems walking about, but no trouble washing or dressing yourself, having no trouble with self-care, no problems performing your usual activities (i.e. work, study, housework, family or leisure activities), no pain or discomfort, not anxious or depressed (21111)	b	Living an average day with mosquitoes as they are now in your yard and porch
3	a	Living an average day with moderate anxiety or depression, but no problem in walking about, no problem with self-care, no problems performing your usual activities (i.e. work, study, housework, family or leisure activities), no pain or discomfort (11112)	b	Living an average day with mosquitoes as they are now in your yard and porch
4	a	Living an average day with some problems in walking about, some problems with self-care, but no problems in performing your usual activities (i.e. work, study, housework, family or leisure activities), no pain or discomfort and not anxious or depressed (22111)	b	Living an average day with mosquitoes as they are now in your yard and porch
5	a	Living an average day with some problems with self-care, moderate anxiety or depression, but no trouble walking about, no problems performing your usual activities (i.e. work, study, housework, family or leisure activities), no pain or discomfort (12112)	b	Living an average day with mosquitoes as they are now in your yard and porch

In the third approach, visual analogue scale valuation, we used a rating scale to derive preference weights and create an interval scale (Parkin and Devlin, 2006). We asked residents to rate mosquito acceptability during a typical 2010 summer week on a scale from 100 (referring to no mosquitoes–best scenario) to 0 (referring to an invasion of mosquitoes–worst scenario).

As presented in Table 2.4, 14% of respondents preferred living an average day with a wrist fracture than living an average day with mosquitoes as they were on a typical 2010 summer day in the respondent's yard and porch, and 41% preferred being in a state where they have some problem performing usual activities to living an average day with mosquitoes. The average disease states trade-off mosquito abundance utility score was 0.79, corresponding to a disability weight of 0.21, which is close to the disability weight attributed to moderate diarrhoea (0.20). The average EuroQol state trade-off mosquito abundance utility score was 0.87, corresponding to a utility loss of 0.13. Using the visual analogue scale, the average residents' mosquito acceptability score was 56.74.

WTP for AWPM and for an extra mosquito-free hour

In New Jersey, we conducted two telephone surveys to estimate the benefit of AWPM. In the first survey, we focused on the programme itself. In the second survey, we valued the benefits associated with the AWPM programme, i.e. an additional hour an adult resident spent enjoying yard and porch activities free of mosquitoes during a typical summer week.

Table 2.4. Percentage of respondents rating an average day with mosquitoes during the summer of 2010 as worse than the comparator state in state trade-off (STO) study.

Comparator state	Utility score	% of respondents
Disease STO (average utility)		
Severe hearing loss	0.968	12%
Wrist fracture	0.935	14%
Influenza	0.790	13%
Bronchitis	0.790	8%
Stomach flu	0.719	10%
EuroQol STO (average utility)		
11211: Some problems performing usual activities	0.888	41%
21111: Some problems walking around	0.880	33%
11112: Moderately anxious	0.876	26%
22111: Some problems walking around, and some problems with self-care	0.823	30%
12112: Some problems with self-care and moderately anxious	0.815	21%

To estimate the perceived benefits of the AWPM, we conducted a telephone survey for a random sample of residents in Mercer and Monmouth Counties between October 2008 and January 2009. The instrument consisted of two main questions, a WTP section, and questions about the use of yard and porch activities. The introduction and WTP questions are presented below.

After receiving an introduction noting the challenges facing urban mosquito control authorities and the potential effectiveness of the AWPM programme, interviewees were asked if they would be willing to support this programme financially by paying an additional tax dedicated for this purpose. Persons with negative responses to the initial question were asked if they would be willing to support this programme financially by making regular charitable contributions. If the answers to both these questions were negative, then these respondents were asked for the reasons for their unwillingness to contribute. For those willing to contribute for the project, we asked about the maximum amount that they were willing to pay using a split sample bidding technique to elicit the maximum amount they would be willing to pay per person per month above and beyond the existing payments for their county's routine mosquito control programme (Stalhammar, 1996). The sample was divided into three components, each assigned to one of the starting values: a high value of $0.75 per person per month, a middle value of $0.25 per person per month and a low value of $0.10 per person per month. This varied starting point controls for possible anchoring bias due to the starting bidding point.

Instrument to Estimate WTP

The instrument was introduced by the following explanatory cover letter.

> Rutgers and Brandeis Universities along with Mercer and Monmouth Counties and the US Department of Agriculture are requesting your response to the following survey about mosquito control, especially a newly introduced day-biting mosquito called the Asian tiger mosquito, which can make outdoor activities very unpleasant.
>
> This interview should take 20 minutes to complete. You were carefully chosen to ensure that we receive responses from a representative group of residents. Completing the survey will help your county and other areas across the country improve their mosquito control programs. It may increase your awareness of ways to protect yourself and your family.
>
> This survey primarily concerns outdoor summer activities and purchases for controlling mosquitoes. Many questions refer to the "selected child" in your household. If there is only one child in your household, then he or she is the selected child. If there is more than one child in your household, then the oldest child in elementary school (if any) is the selected child. Finally, if no children are in elementary school, then the oldest child is the selected child for the survey.
>
> Participation in this survey is voluntary; you can skip any questions you don't want to answer or don't feel comfortable with. We will send you $10 in cash on completion of the survey in recognition of the

> value of your response. Your response will be used only for this study and will be kept confidential…

The description began with a hypothetical scenario, followed by a series of questions.

> Introduction: We would like to begin with some questions that could assist public officials in determining how to improve the mosquito control services in your neighborhood. Currently, your county spends about $0.25 per person per month to control other types of mosquitoes. However, the measures taken are not effective in controlling urban mosquito species, including the Asian tiger mosquito. Your county is considering plans to implement an area-wide pest management program that would drastically decrease the population of urban mosquitoes, thereby reducing the potential threat of disease and nuisance from their bites.

The instrument then asked the following questions:

> i1. Would you be willing to support this program financially by paying an additional tax earmarked for this purpose?
> _____ Yes (go to question 4) ______ No
>
> i2. Would you be willing to support this program financially by making regular charitable contributions for this purpose?
> _____ Yes (go to question 4) ______ No
>
> i3.What, if any, are the reasons for your unwillingness to contribute? (Please check all responses that apply)
> a. This program is of no value to my household
> b. I currently do not have a mosquito problem
> c. I prefer personal control measures
> d. The state should cover the expenses from other programs
> e. Other groups in the society should pay
> f. I cannot afford it
> g. I prefer other ways of paying
> h. Other
>
> i4. Use the diagram given by the study manager for this interview. Record the figure number: _____

Results of WTP for AWPM Programme

The average WTP per person per month was $0.49, in 2018 US$. Residents in Monmouth County were willing to pay $0.28 per person per month, compared with $0.76 per person per month in Mercer County, as shown in Table 2.5. The aggregate annual WTP in these two counties was $5.9 million, more than double the amount budgeted in 2008. These results highlight the importance of mosquito control activities from the perspective of those two counties' residents.

When we compared our sample to the population in these two counties, we found they differ in the distribution of households between those two counties and in the age of respondents (Halasa *et al.*, 2012). As a sensitivity analysis, we weighted the WTP by county population and by age. In all cases, the average per person per year WTP amount was higher than the mosquito control budget at baseline (Table 2.6). The WTP would increase the counties' budgets by 209% in the naïve analysis, 195% after adjusting for county population and 168% after adjusting for age.

Table 2.5. Average amount telephone respondents were willing to pay (WTP), Mercer and Monmouth Counties' budgets for mosquito control in 2008 and the aggregate annual WTP compared with annual budget, in 2018 US$.

	Monmouth	Mercer	Both counties
Number of respondents	29	22	51
Average WTP for all respondents per person per month ($)	0.28	0.76	0.49
Average WTP per person per year ($)	3.33	9.11	5.83
Population			
Census population (2008)	642,448	364,883	1,007,331
Aggregate WTP per month ($)	178,501	277,093	489,199
Aggregate WTP per year ($)	2,142,017	3,325,114	5,870,390
Current budget			
2008 budget per person per year ($)	3.11	2.22	2.79
2008 budget for all mosquito control ($)[a]	1,999,405	810,632	2,810,037
% Increase in current county budget (%)	107	410	209

[a] Mercer County 2008 budget: County of Mercer, Department of Transportation and Infrastructure, Division of Highways, Mercer County Mosquito Control, Plans and Estimates 2008.

The Monetary Value of an Additional Hour an Adult Resident Spends Enjoying Yard and Porch Activities Free of Mosquitoes During a Typical Summer Week

To estimate the AWPM benefit in reducing mosquito nuisance, we used the contingent valuation approach to estimate the maximum WTP amount an adult resident would pay for an additional mosquito-free hour in their yard or on their porch. We asked respondents to rank five porch and yard activities (Fig. 2.2) (i.e. eating and cooking outside, playing, relaxing and socializing, gardening, and maintaining their car or house), and to state the maximum amount they were willing to pay for one additional hour engaged in each of these activities with reduced mosquito nuisance. We started the bid with $1. Four cases (3.3% of our sample) reported extreme values (over $100 per porch or yard activity). We adjusted for these extreme values by annualizing WTP values to the variable's 95th percentiles.

> I want you to think of the following yard and porch activities. How much do you enjoy participating in these activities in your yard or around your home? Please rate them from 1 to 5, where 1= do not enjoy at all and 5 = enjoy them a great deal.
>
> Now, I will ask you a few questions about an imaginary hour and how you would use it. I want you to imagine that you have one additional work-free hour each summer week to spend doing yard and porch activities. This could occur if you got out of work or school an hour earlier, the traffic or buses were faster or you finished your household tasks sooner. This hour would be free of responsibilities and available only for your pleasure and enjoyment. Furthermore, I want you to think of it as a one mosquito-free yard and porch hour. If you could spend this hour doing just one of the following activities, which one would you choose?
>
> a. Eating or cooking outside.
> b. Playing catch, frisbee, bocce, horseshoes, croquet, volleyball, etc.
> c. Relaxing, socializing, talking, reading, hanging out, etc.
> d. Gardening or mowing lawn.
> e. Maintaining house or car.
>
> Now I would like to know how much this additional hour is worth for you. By having a value for this hour we will be able to understand your preferences and help policy makers develop policies that address these preferences.
>
> Would you be willing to pay $1 to have one additional hour for DOING ACTIVITY X? (Use Fig. 2.3 as a guide).

Table 2.6. Sensitivity analysis addressing the variation in the distribution of households in Mercer and Monmouth Counties and age of respondents, in 2018 US$.

	Unadjusted	Adjusted by county population	Adjusted by age groups
Number of respondents	51	51	51
Average WTP per person per month ($)	0.49	0.45	0.39
Average WTP per person per year ($)	5.83	5.43	4.70
Aggregate WTP per year ($)	5,870,390	5,467,387	4,734,190
Mosquito control budget, baseline			
2008 budget per person per year ($)	2.79	2.79	2.79
2008 budget for all mosquito control ($)	2,810,037	2,810,037	2,810,037
% Increase in 2008 budget for the two counties combined	209	195	168

WTP denotes willingness to pay.

a. Eating or cooking outside	1	2	3	4	5
b. Playing catch, frisbee, bocce, horseshoes, croquet, volleyball, etc.	1	2	3	4	5
c. Relaxing, socializing, talking, reading, hanging out, etc.	1	2	3	4	5
d. Gardening or mowing lawn	1	2	3	4	5
e. Working on or repairing your house or car	1	2	3	4	5

Fig. 2.2. The instrument used to estimate the maximum willingness for an additional hour engaged in yard or porch activities with reduced mosquito nuisance.

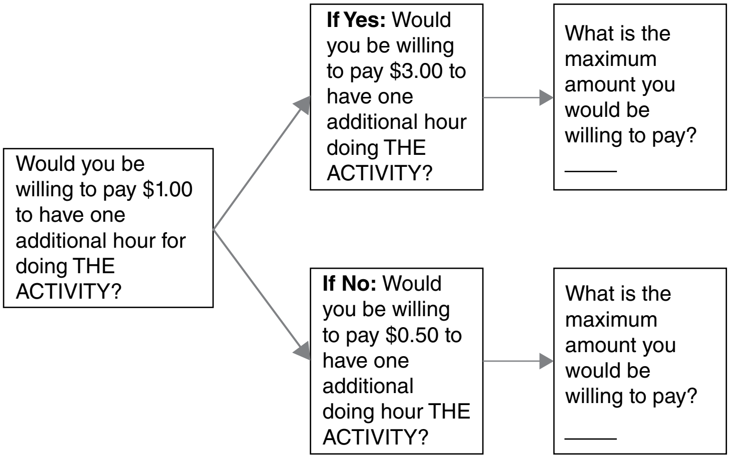

Fig. 2.3. A chart to assist in capturing the maximum amount the respondent is willing to pay.

The survey next asked the interviewer to repeat the importance and value of an additional hour for each yard and porch activity to capture the maximum WTP amount for each of these yard and porch activities.

Results: WTP for an Additional Mosquito-Free Hour Engaged in Yard and Porch Activities

Relaxing and socializing in the yard or porch was rated as the most important (89.2%), followed by eating and cooking outside (82.7%). Figure 2.4 illustrates the yard and porch activities rated as very important or important. The ranking of these activities by importance reflects the enjoyment respondents perceived in engaging in these activities. When asked for the maximum amount respondents were willing to pay for one additional imaginary work-free, mosquito-free hour per summer week engaged in these activities, the ranking of the average maximum amounts they were willing to pay was very similar to the enjoyability ranking. We found one exception in gardening ($8.58), which was ranked fourth but the amount was 6.6% higher than the amount they were willing to pay for playing in the yard ($8.05). Figure 2.5 presents the results.

We used our pooled survey data for the years 2008 through 2011 and the results from the WTP survey. For each observation, we calculated the product of the hour lost enjoying or engaging in each yard or porch activity (discussed in the effectiveness section) with the maximum amount residents were willing to pay to enjoy this additional hour without mosquitoes (discussed in the WTP section, above). We then summed the product of the five activities to get the total WTP for each observation, and reported the average total maximum WTP amount. Table 2.7 presents the maximum WTP amount, or the preserved benefits of the AWPM as stated by the residents of Mercer and Monmouth Counties in New Jersey. The 3.30 h per week gained enjoying yard and porch activities are equivalent to statistically significant perceived benefits of an adjusted $30.36 per week. Extrapolating these results to a 13-week summer results in a gain of 42.96 h and a monetary valuation per adult resident of $394.62 per year.

Economic evaluation of AWPM in New Jersey

In this economic evaluation, we evaluate both the incremental costs and outcomes of the intervention. We utilized three economic evaluation approaches to determine the impact of the AWPM on residents' enjoyment of their yards and activities in those two counties. For the cost analysis, Table 2.1, we estimated the incremental annual cost of the programme at $37.19 per person. As indicated in Table 2.3, the additional hours of yard and porch activities gained due to AWPM were 3.3 h/week (or 42.96 h over a 13-week summer) in the AWPM areas compared with the control areas. This is translated into a cost-effectiveness ratio of $0.87 per hour gained.

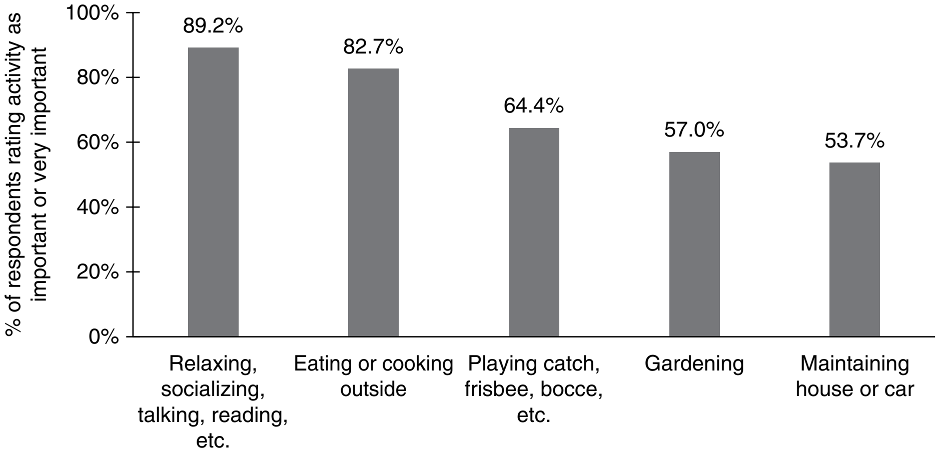

Fig. 2.4. Yard and porch activities rated as very important or important.

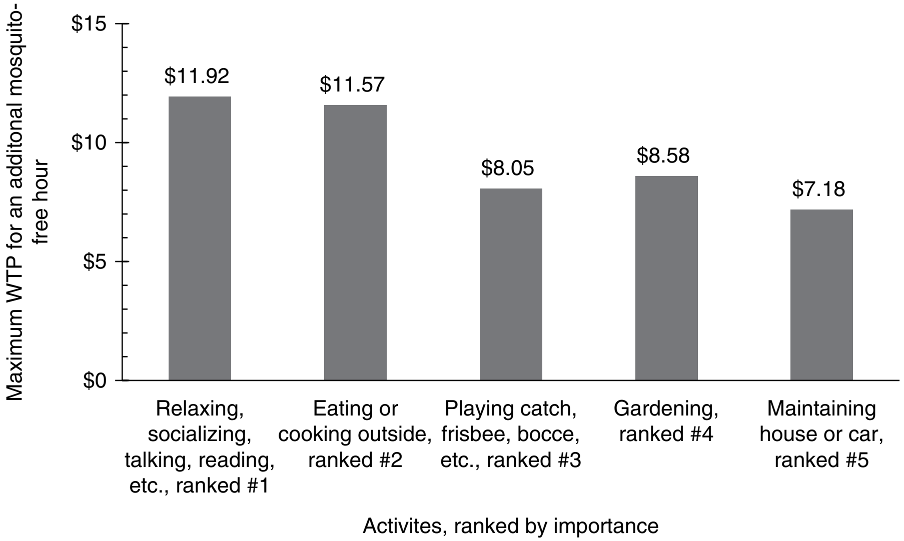

Fig. 2.5. Maximum willingness to pay, in 2018 US$, for an additional work-free, mosquito-free hour in a typical summer week engaged in yard and porch activities.

The perceived value of this gain was valued at $30.36 per week or $394.62 for a 13-week summer (Table 2.5). This translates into a cost–benefit analysis of $10.61 gained for each $1 spent on the AWPM. The mosquito abundance utility score of individuals living in the AWPM areas was 0.8753, compared with 0.8645 in control areas during the summer of 2010. That is, the lower abundance of mosquitoes in AWPM areas translated to residents' greater enjoyment of yard and porch activities (i.e. higher utilities). An average resident's increased utility from the AWPM programme was 0.0108 (i.e. 0.8753–0.8645). The average resident experienced this added enjoyment for 0.25 years (i.e. the 13-week summer divided by the 52-week year). Therefore, his or her incremental annual quality adjusted life years gained was 0.0027 (i.e. 0.0108 × 0.25). This increase in utility translated into a

Table 2.7. Pooled ordinary least squares regression with cluster-robust standard errors of the value lost due to mosquitoes in 2018 US$.

Independent variables	Total hours		Value lost due to mosquitoes ($)		Reference category
Study years					
Year 2009	17.17	***	167.65	***	Year 2008
	(10.63)		(11.23)		
Year 2010	0.76		5.48		
	(0.78)		(0.59)		
Year 2011	16.13	***	155.94	***	
	(11.34)		(11.89)		
Assigned intervention areas	–3.30	*	–30.36	*	Assigned control areas
	(2.35)		(2.34)		
Study areas					
AWPM_baseline, cluster 1	2.28		22.49		Cummings (Mercer control area)
	(1.21)		(1.29)		
AWPM_baseline, cluster 2	1.96		18.84		
	(1.26)		(1.32)		
Control_baseline	0.40		2.28		
	(0.29)		(0.18)		
Attainment of a bachelor's degree or higher	–3.18	**	–33.27	**	Respondents with less than bachelor's degree
	(2.74)		(3.15)		
Constant	6.91	***	78.73	***	
	(6.30)		(7.64)		
Effectiveness of AWPM	3.30		30.36		
Hours lost in 2008	9.09		86.00		
% gained due to AWPM	36.4%		35.3%		
Observations	1581		1581		
R-squared	13.88%		12.95%		

t-value in parentheses (ignoring sign); *denotes $p < 0.05$, **denotes $p < 0.01$, ***denotes $p < 0.001$; the regression also includes interaction terms between year and study area to measure the differential changes in mosquito control by area (coefficients not shown here). AWPM denotes area-wide pest management.

cost–utility ratio of $13,774 per quality adjusted life years gained per person (i.e. $37.19/0.0027 = $13,774).

A widely cited guideline from the World Health Organization suggests that if the cost per quality adjusted life years gained is below the country's per capita GNP, then the intervention could be considered highly cost effective and generally deserving of inclusion in publicly funded programmes to support health (Bertram *et al.*, 2016). The latest per capita gross national income for the United States is $59,532 (World Bank, 2018). As $13,774 is only one-quarter of the country's per capita gross national income, it easily meets this criterion. As those authors noted, other factors, such as feasibility and equity, are also important (Bertram *et al.*, 2016). However, AWPM also rates favourably on these criteria as well. Based on both cost-effectiveness and other criteria, the AWPM is a very good use of public resources.

Conclusions

This chapter has demonstrated that economic analysis is an important component of the evaluation of an integrated pest management programme, and proved important in the application to AWPM in Mercer and Monmouth Counties, New Jersey, USA.

A comprehensive economic evaluation, such as the one we endeavoured to implement on AWPM in New Jersey, requires multiple types of data. A key strength of economic analysis is its ability to draw on diverse types of data from different sources. The analysis also provides transparency, as each data source is carefully documented. The case study of AWPM in New Jersey was built on three types of data. The first was cost data. These were obtained from the incremental annual costs of mosquito control activities attributable to *Ae. albopictus* in the intervention counties in the intervention years compared with the pre-intervention years. To standardize these costs, each was expressed in terms of cost per person per year.

The second type of data concerned the impact of the programme on house and yard activities. As *Ae. albopictus* did not involve a risk of disease in New Jersey, the AWPM's benefit occurred through an improvement in residents' quality of life through being better able to enjoy their summer outdoor activities. This was assessed through surveys in intervention and control sites in the two counties documenting hours lost from outdoor activities due to *Ae. albopictus*. To our knowledge, this study was the first time that researchers had assessed the improvements in quality of life from a mosquito control programme.

The third type of data concerned placing economic values on these outcomes. These were obtained from WTP surveys, which assessed the value that residents placed on a 'mosquito-free hour' and the value they would place generally on an effective mosquito control programme. The overall economic benefits were the product of the net number of summer outdoor hours gained times the value of each such hour. The analysis then compared the incremental benefits of the programme with its incremental costs, both expressed in monetary terms.

The AWPM, as implemented in New Jersey, was a repeated short-term programme. Each year, the programme advised residents about source reduction, conducted community clean-up programmes, and treated adult mosquitoes and larvae with insecticide in public areas. Potentially, a longer-term approach with a redesign of the urban landscape and legal changes might achieve comparable results at lower long-term costs. For example, legal changes could empower local governments to enter and clean up abandoned houses, putting the cost as a tax lien and, if necessary, selling the property if the owner did not pay. Residents could be discouraged from installing bird baths in their yards, thereby avoiding the need to change the water every 7 days. Residents could ensure drainage around flower pots so that standing water could not accumulate in the plant saucers. As storing tyres outdoors accumulates rainwater, which breeds mosquitoes, governments could impose a deposit on new tyres, much like those existing for bottles for carbonated beverages. This deposit would create an incentive for individuals and local organizations to collect and recycle old tyres. Similarly, local government could require residents to keep the exteriors of their yards free of trash, much like they are responsible for clearing snow from their sidewalks after a snowstorm. Some foreign countries, such as Singapore, Switzerland and Rwanda, are renowned for public cleanliness.

The AWPM evaluation benefited from the involvement of economists throughout the course of the study. This involvement proved critical in several ways. First, the collection of economic data required interviewing mosquito control programme officials in both counties. While financial reports showed the aggregate expenditures and budgets, the needed breakdown of the shares of these costs related to *Ae. albopictus* control was available only through such interviews. Second, the collaboration between economists and other researchers led to the design of several rounds of household surveys of residents in intervention and control areas, both before and after the AWPM. These data could not have been obtained retrospectively or through existing documents.

Finally, in the same way as the data needs in this study benefited from multiple sources in the literature, the evaluation of the AWPM in New Jersey is informing efforts elsewhere. For example, policy makers in the state of Queensland, Australia, have been fearful about the establishment of *Ae. albopictus* in their state. The New Jersey experience provided data for estimating the economic benefits of keeping Queensland free of this mosquito (Darbro *et al.*, 2017).

This chapter suggests four types of implications for future innovations on integrated vector control. First, the methods used here could be more widely applied. They entailed assessing an intervention's cost, its effect on abundance of mosquitoes and the resulting impact on residents' quality of life, for which the New Jersey case study provided a scale. Second, the case study demonstrates the importance of including an economist from the outset in the research team, so that costs are measured and monitored throughout the intervention's development and implementation. Also, the science of economics highlighted the need for carefully defining outcome measures to be able to analyse trade-offs. Third, the case study provided evidence that integrated vector control yields a favourable economic return on the measures included. Finally, the case study identified a number of extensions that future studies could address with additional methodology and data. These include estimating impact on tourism, possible offsets to household expenditures on pest management, and concern due to current and possible future mosquito-borne illness.

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3

What Can We Learn from More Recent (and More ‘Rigorous’) Economic Impact Assessments of Integrated Pest Management Farmer Field Schools (IPM-FFS)?

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Overuse of chemical pesticides and its consequent negative effects on human health and the environment have been a recurring concern in agriculture over the past 50 years (Pingali *et al*., 1994). In light of this situation, integrated pest management (IPM) has been developed in many countries where a mixture of cultural, biological and/or chemical techniques to control pest populations is promoted as an alternative option for farmers (i.e. to reduce reliance on purely chemical approaches for pest control).

Given the variety of principles and practices involved in an IPM approach, farmers typically need to process and understand a large amount of information to successfully implement an IPM control programme in their operations. As such, advocates of these IPM methods also usually conduct complementary extension, training and/or information dissemination programmes to facilitate adoption and diffusion of the IPM technique. However, the more traditional, ‘top-down’ extension approach to disseminating IPM information has historically been viewed as less effective when disseminating knowledge-intensive IPM techniques (Gautam and Anderson, 2000; Waddington and White, 2014). Therefore, a more participatory training approach through IPM Farmer Field Schools (IPM-FFS) was developed to better communicate IPM concepts and practices to farmers, and for them to better internalize and adopt these IPM control methods. Since the first IPM-FFS project was implemented in 1989 for Indonesian rice farmers, the IPM-FFS format has been implemented in over 90 countries worldwide and over 12 million individuals have graduated (Waddington and White, 2014).

The key characteristic of IPM-FFS is its experiential learning approach where participants are given the opportunity to help identify core pest management issues that need to be addressed by the curriculum and where ‘group learning’ is encouraged to solve specific pest problems. The typical IPM-FFS training involves a field-based, season-long programme overseen by an IPM-FFS facilitator (or trainer), with weekly meetings near the plots of participating farmers. For the whole growing season, participants visit their fields weekly and congregate thereafter to discuss field activities/observations particularly with respect to insects and pests. In the classroom, farmers are then typically taught by pest experts how to manage the observed insect and pest activity through IPM techniques. This knowledge is then applied by the participant in their fields under the guidance of the trainers. Post-evaluation of the method is also undertaken weekly to inform other farmers on the method and its effectiveness. This

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evaluation is usually undertaken in the fields by having some plots designated as 'IPM-managed' and other plots as 'business-as-usual', traditional chemical practice plots. The training lasts until the end of the harvest season. Aside from experiential learning approaches, the IPM-FFS programmes also sometimes use pamphlets and brochures in addition to lectures. Samples of the materials needed for biological control are also usually distributed, so that participants can study and test it in their fields.

With the widespread adoption of IPM-FFS worldwide, there have also been hundreds of studies that have evaluated the effectiveness of the IPM-FFS approach for specific countries, crops and/or contexts. In particular, most of these evaluation studies are interested in the economic impacts of IPM-FFS, such as its effects on the level of chemical pesticide use, yields and revenues (or profits/net income). But given the volume of studies, as well as the different evaluation approaches and contexts, the evidence from this huge literature has been decidedly mixed (i.e. some studies found positive, statistically significant impacts, while others did not find any statistically significant effects).

An especially useful recent study is that of Waddington *et al.* (2014), where they systematically reviewed the full IPM-FFS economic evaluation literature through 2012 and attempted to draw conclusions from this body of knowledge. An important finding in their study is that, among the hundreds of studies they vetted, only 15 studies were found to be 'sufficiently rigorous to qualify as medium risk of bias' (see p. 65 in Waddington *et al.*, 2014). These 15 economic impact evaluation studies used multivariate estimation techniques (i.e. characterized as 'quasi-experimental' statistical approaches) that attempted to appropriately control for selection bias, confounding factors and other sources of bias that can affect the credibility and accuracy of the estimated IPM-FFS impacts. Note that the majority of the studies examined by Waddington *et al.* (2014) were considered to have a 'high risk of bias' (i.e. these studies did not have proper 'comparison' groups, and/or did not appropriately control for selection issues), and no study was found to have a 'low risk of bias' (i.e. using a fully 'experimental' randomization approach such as through a randomized control trial (RCT)).

Based on results from the 15 'medium risk of bias' studies (and statistical 'meta-analysis' techniques of results from these studies), Waddington *et al.* (2014) concluded that IPM-FFS are generally effective in improving intermediate economic outcomes for participating farmers in smaller-scale programmes. On average, IPM-FFS programmes in these studies were shown to provide the following: a 39% reduction in insecticide use (i.e. based on an environmental impact quotient), a 13% increase in yields and a 19% increase in net revenues (or profits). However, these economic impacts are only found in smaller-scale programmes, and were not observed for IPM-FFS programmes that were scaled up to the national level. In addition, based on two studies that compared the benefits and costs of IPM-FFS programmes, Waddington *et al.* (2014) also indicated that IPM-FFS approaches are unlikely to be a cost-effective method for extending complex IPM information.

In light of this comprehensive review by Waddington *et al.* (2014), the objective of this chapter is to 'build on' this previous work and examine more recent (e.g. 2012–2016) economic impact evaluation studies of FFS (i.e. those not included in the Waddington *et al.* 2014 study). In particular, the focus is on recent economic impact studies that utilized 'more rigorous' evaluation techniques that account for selection issues/bias (i.e. 'medium-' to 'low-risk of bias'), especially those studies that utilized quasi-experimental techniques and/or fully experimental RCT approaches to evaluating FFS interventions. As the question posed in the title of this study asks: are there new and additional insights from these more recent and more 'rigorous' 2012–2016 studies that were not captured in the systematic review by Waddington *et al.* (2014)? We are also interested in whether these more recent studies followed some of the recommendations coming out of the Waddington *et al.* (2014) paper. Lastly, we also hope to provide some recommendations that are directly relevant to entomologists and other scientists developing IPM practices, IPM-FFS programmes, and other educational programmes promoting the use and diffusion of this pest control strategy.

Methods: Structure of the Review Approach

The first step in our review process was to search relevant databases for 2012–2016 studies that evaluate potential economic impact(s) of IPM-FFS. Given the economic impact focus of this review, the Econlit database was the first one searched since it is considered the main database for the field of economics. The initial keywords used for the search were 'Farmer Field Schools' and/or 'IPM-FFS'.

About 68 studies were listed in this initial search, but only 12 studies were actually related to economic impact evaluation of FFS (or IPM-FFS specifically). Among these 12 studies, however, four studies were already considered in the aforementioned Waddington *et al.* (2014) systematic review and three more did not utilize 'more rigorous' experimental or quasi-experimental statistical approaches (i.e. high risk of bias). The four studies previously considered in the Waddington *et al.* (2014) study were still not formally published at the time their systematic review was conducted (i.e. they were just working papers and/or were still not accepted for journal publication). The four papers excluded in our current review are: Ali and Sharif (2012), Davis *et al.* (2012), Todo and Takahashi (2013) and Carlberg *et al.* (2014). Moreover, the three 2012–2016 studies that did not utilize 'more rigorous' statistical techniques in the evaluation of IPM-FFS (and also excluded in the current review) are: Chandra *et al.* (2017), Harris *et al.* (2013) and Kariyasa (2014). Thus, these seven studies were excluded in our analysis and only the remaining five studies were included in the current review since they all utilize 'more rigorous' impact evaluation methods (i.e. use of experimental or quasi-experimental approaches to control for selection bias), which is a vital criterion for this review.

The second database searched was Agricola, which is one of the main databases for general agriculture-related studies and journals (e.g. entomology, agronomy, etc.). Several of the 12 2012–2016 studies found in the initial search of the Econlit database were also listed in the Agricola database. However, there were two additional 2012–2016 studies that were listed in Agricola that were not found in the initial Econlit search. Of these two, only one of them utilized 'more rigorous' econometric methods that attempt to control for selection bias through experimental and/or quasi-experimental approaches. The excluded study from the Agricola database search is Sharma *et al.* (2015). This lone study from the Agricola database was included in the current review.

Further examination of this lone included study from the Agricola database also led us to a prior, more comprehensive impact evaluation study from the same set of authors. This additional study also used a 'more rigorous' statistical approach to evaluate the impact of FFS on different economic outcomes, although it is still an unpublished manuscript (i.e. looks like a working paper and/or project report). Thus, a total of seven 2012–2016 'more rigorous' studies that evaluate the impact of FFS are included in the present review (See Table 3.1). Note that the papers by Bonan and Pagani (2016), Larsen and Lilleor (2014), Masset and Haddad (2015), Sanglestsawai *et al.* (2015) and Tsiboe *et al.* (2016) were the ones found based on the initial Econlit search, while the studies by Guo *et al.* (2015)

Table 3.1. List of seven studies included in the present review study.

Author(s) (year)	Title	Source/journal
Bonan and Pagani (2016)	Junior Farmer Field Schools, agricultural knowledge and spillover effects: quasi-experimental evidence from northern Uganda	U. of Milan working paper
Burger *et al*. (2015)	Assessing the impact of Farmer Field Schools on fertilizer use in China: evidence from a two-province randomized experiment	Unpublished manuscript/ report (based on a project funded by 3ie)
Guo *et al*. (2015)	Farmer Field School and farmer knowledge acquisition in rice production: experimental evaluation in China	*Agriculture, Ecosystems and Environment*
Larsen and Lilleor (2014)	Beyond the field: the impact of Farmer Field Schools on food security and poverty alleviation	*World Development*
Masset and Haddad (2015)	Does beneficiary farmer feedback improve project performance? An impact study of a participatory monitoring intervention in Mindanao, Philippines	*Journal of Development Studies*
Sanglestsawai *et al*. (2015)	Economic impacts of integrated pest management (IPM) Farmer Field Schools (FFS): evidence from onion farmers in the Philippines	*Agricultural Economics*
Tsiboe *et al*. (2016)	Estimating the impact of farmer field schools in sub-Saharan Africa: the case of cocoa	*Agricultural Economics*

and Burger *et al.* (2015) were primarily found through the Agricola search.

One important issue to mention is that not all the studies included in our review solely focus on the use of FFS to disseminate IPM information (i.e. not solely IPM-FFS). A number of studies evaluate FFS that disseminate more general agricultural information meant to improve overall livelihoods of farm households. IPM may only be a small part of the FFS programme being evaluated. In addition, some studies only focus on certain non-pest management-related economic outcomes, like fertilizer use, non-pest management-related knowledge, poverty and/or food security outcomes. However, most of these studies still evaluate effects of FFS on yields and/or input use. Even though not all programmes are solely focused on IPM (or pest management-related) information dissemination, we still include them in this review and just note whether the programmes being assessed include (or do not include) IPM practices (see the next two sections). Important insights and implications can still be gleaned from these non-solely IPM-focused programmes, which may still be applicable for IPM-focused FFS.

Descriptive information on the studies reviewed

Table 3.2 provides brief descriptions of each paper included in the current study. As mentioned above, not all studies evaluate FFS programmes aimed solely at imparting IPM-related practices. However, all of these studies evaluate the effect of specific FFS approaches on economic outcomes that have been tied to IPM-focused FFS in the past. In this section, we briefly describe each study included in our review.

Bonan and Pagani (2016) examine the effect of 'Junior' FFS (JFFS) in Uganda that specifically disseminate information about agricultural practices to elementary school kids of farming households. The idea is for these children to improve their knowledge about agricultural practices, then transmit some of this information to household adults, and consequently improve overall household agricultural production. A difference-in-differences (DID) approach augmented with propensity score matching (PSM) (i.e. to control for endogeneity and selection bias) were the research methods utilized and applied to a 2-year 'baseline with follow-up' dataset. Overall, Bonan and Pagani (2016) show that the JFFS have a statistically significant positive effect on student knowledge, student's adoption of agricultural practices, knowledge transmission to parents and on household nutrition. However, no statistically significant effects were found with regard to total household agricultural production (i.e. total production in terms of number of crops grown rather than yields).

Burger *et al.* (2015) and Guo *et al.* (2015) are two of the three studies in this review that utilized a fully experimental RCT approach that is considered by Waddington *et al.* (2014) as 'low risk of bias' (and is generally considered as the 'most rigorous' approach for evaluating FFS). As noted above, the Guo *et al.* (2015) article is a 'sub-project' of the overall RCT evaluation reported in Burger *et al.* (2015). For the whole project, village-level randomization was conducted where 46 villages located in two Chinese provinces were randomly selected as the treatment group (i.e. where a fertilizer-focused FFS programme was provided) and 46 villages were used as the control group (i.e. with no FFS programme provided). Data were collected pre-FFS and post-FFS.

Guo *et al.* (2015) mainly provided results about the impact of the FFS programme on knowledge acquisition for a sample of Chinese rice producers (i.e. in only one of the provinces included in the overall project). Although the FFS programme was focused more on nutrient management practices, the programme also provided lessons about pest management, cultivation and agriculture-based environmental problems. As such, the impact of FFS programmes on knowledge was evaluated based on test scores for these four general areas. Results of the RCT evaluation of FFS in Guo *et al.* (2015) indicate that there is statistically significant improvement in knowledge. But the effect is heterogeneous since knowledge improvement was observed only for two of the four component areas (i.e. pest management and cultivation). Moreover, Guo *et al.* (2015) report that the FFS impact on knowledge works best only for particular sub-groups (e.g. young male farmers), and no evidence of knowledge spillover was found. Overall, given the lack of overwhelming positive knowledge effects, Guo *et al.* (2015) was hesitant to recommend broad-based scale-up of FFS as an extension tool without improvements to better reach other key farmer populations.

As compared with the Guo *et al.* (2015) article, which only focused on the knowledge effects of FFS for a sample of Chinese rice farmers, the Burger *et al.* (2015) publication more comprehensively

Table 3.2. Descriptive information on the seven studies included in the review.

Study/authors	Location	Type of Farmer Field School (FFS) intervention	Study arms/years analysed	Methods and year(s) of analysis	Sample size	Main findings/economic outcomes
Bonan and Pagani (2016)	Uganda	Junior FFS (JFFS) for elem. school children); gen. ag. focus, includes IPM; multiple crops	JFFS vs non-JFFS (students & guardians)	DID & DID with PSM, 2012–2013	211	+ effect on student knowledge, + knowledge spillover to guardians, + effect on nutrition, no sig. effects on household production
Burger *et al*. (2015)	China	FFS, fertilizer focus (not including IPM, except pest mgt. knowledge), rice & tomato	FFS vs non-FFS (also FFS & ‘exposed’ to FFS vs non-FFS)	Cluster RCT, 2011–2013	Rice = 715; Tomato = 399	Insignificant effect on fertilizer (for full sample), but – effect on distance to ‘optimal’, + effect on knowledge (including IPM), no effect on rice yields, + effects on tomato yields
Guo *et al*. (2015)	China	FFS, focus on knowledge effects (subset of Burger *et al*., 2015 study), rice	FFS vs non-FFS	Cluster RCT, 2011	711	+ overall effect on knowledge, + effect on pest management knowledge and agri-environment problems
Larsen and Lilleor (2014)	Tanzania	FFS, focus on improving livelihoods (food security and poverty), IPM not included, banana & livestock	FFS vs non-FFS	Quasi-DID, matching, intention-to-treat analysis, 2007 & 2011	2041	+ food security effect (in terms of reducing hunger, increased no. of meals, intake of animal protein), no effect on poverty
Masset and Haddad (2015)	Philippines	FFS, focus on effect of feedback mechanisms in FFS, gen ag. programme (IPM not included), cocoa, coconut, rice	FFS with feedback mechanism vs FFS only vs non-FFS	RCT (of feedback component), 2011–2012	1233	+ effect of FFS & FFS feedback mech. on agricultural knowledge and adoption of practices, no effect on yields, effect on knowledge increase as attendance increase
Sanglestsawai *et al*. (2015)	Philippines	IPM-FFS, FFS focused on IPM, onion	FFS vs non-FFS	Matching (PSM), 2009	197	– effect on insecticide expenditures, no effect on yields, labour, herbicide, fertilizer and profit
Tsiboe *et al*. (2016)	Sub-Saharan Africa	FFS, focus on yields, cocoa	‘Full’ FFS (FFS with business training & input credit) vs not exposed to ‘full’ FFS	DID, 2009/10 & 2012/13	2048	+ effect on yields only for exposed to ‘full’ FFS package (i.e. FFS only without business training & input credit has no significant effect)

FFS, Farmer Field School; DID, difference-in-differences; IPM, integrated pest management; PSM, propensity score matching; RCT, randomized control trial; JFFS, Junior Farmer Field School.

reports on the effects of FFS on other economic outcomes (e.g. fertilizer use, yields), and covers both rice and tomato farmers in two Chinese provinces. In general, Burger *et al.* (2015) found mixed evidence of programme effectiveness across outcomes and the two crops. When looking at the overall mean effects, the RCT analysis in Burger *et al.* (2015) indicates that there was no statistically significant difference in the fertilizer use of FFS-treated farmers relative to the control farmers. However, Burger *et al.* (2015) highlight the importance of heterogeneity in the effects of FFS – farmers that initially used low levels of fertilizer tend to increase fertilizer use after FFS, and farmers that initially used high levels of fertilizer tend to reduce fertilizer use after FFS. This result is supported by a supplementary analysis where Burger *et al.* (2015) found that FFS statistically reduces the 'distance' from the 'agronomist-determined' optimal nitrogen (N) fertilizer application. In terms of yield effects, Burger *et al.* (2015) did not find any statistically significant FFS yield effects for rice, although a significant positive effect was found for tomato. There was also no evidence of spillover effects found in the Burger *et al.* (2015) study. Consistent with the recommendations in Guo *et al.* (2015), Burger *et al.* (2015) do not unambiguously support a broad-based scale-up of the FFS approach due to the mixed RCT-based evidence found.

Compared with other earlier FFS impact studies, Larsen and Lilleor (2014) is unique in that it focuses on the effects of FFS on more 'aggregate' economic outcomes that have previously been unexamined (or only sparsely assessed) – food security and poverty. The particular FFS programme explored in this study was a 3-year general agriculture programme in Tanzania that introduces farmers to a 'basket' of good agricultural practices. Typically, included in this 'basket' are: improved varieties of bananas (and associated cultivation techniques), conservation practices, crop diversification, improved animal husbandry, fruit and multi-purpose trees, soil and water conservation, post-harvest technologies and encouragement to join savings groups. The Larsen and Lilleor (2014) study utilized a matching method and a quasi-DID approach to address selection bias in the impact evaluation. The quasi-DID approach used in this study is different from the standard DID in the sense that a true panel dataset (i.e. same producers surveyed over time) was not utilized. This quasi-DID approach was based on the empirical strategy proposed in Coleman (1999, 2006). The dataset utilized in the study was collected several years after completion of the FFS programme. Results from Larsen and Lilleor (2014) indicate that farmers exposed to the FFS programme generally adopt some of the practices introduced in the 'basket' of options (i.e. farmers pick and choose which practices fit their needs). Consequently, a statistically significant improvement in food security was observed, where hunger is reduced, number of meals to children increased and intake of animal protein increased. However, Larsen and Lilleor (2014) did not find statistical evidence of an FFS effect on poverty (i.e. based on a poverty index and proxy poverty measures related to house flooring and mobile phone ownership). The authors hypothesized that the improvement in agricultural production practices may have resulted in better smoothing of food consumption over time (i.e. affecting food security) rather than acquiring non-food assets (i.e. which mainly affects the poverty measures).

The last RCT-based FFS impact evaluation study included in the present review is by Masset and Haddad (2015). The emphasis in Masset and Haddad (2015) is on evaluating the impact of a specific 'farmer feedback mechanism' included as part of a general agriculture FFS programme in the Philippines. The FFS programme evaluated in this study is a more comprehensive course that provides training for production and marketing of rice, cocoa and coconut. Pest management is only one aspect of this programme. Topics such as general farm management, farm establishment (land preparation and crop establishment), harvest techniques and post-harvest processing are also discussed in this FFS. Data were collected pre-intervention and post-intervention (after a 1-year FFS cycle).

This 'farmer feedback mechanism' aims to improve farmers' awareness of the progress he/she is making in the programme and also gives additional feedback information to FFS programme facilitators as to what works and what does not (i.e. to hopefully adjust to improve FFS performance). Masset and Haddad (2015) randomly allocated the 'farmer feedback mechanism' to 30 FFS programmes, while 29 FFS programmes do not have this feedback mechanism in place. In addition, a control group was also selected where 13 FFS programmes (in ten villages) are planned to be implemented (i.e. no FFS was provided at the time of the study). Hence, the impact of FFS itself (with and/or without the feedback component) was evaluated as well (relative to the non-FFS control group). Results of the RCT analysis in Masset and Haddad (2014) show that FFS have a positive statistically significant impact on agricultural knowledge of participants (relative to the control group), as well as on the adoption of good agricultural practices promoted by the FFS programme. However, there were no statistically significant effects of FFS on yields. The 'farmer feedback mechanism' also had an additional statistically significant effect on knowledge and practices, but still no effect on yields. Masset and Haddad (2014) also show that increasing farmer attendance enhances the FFS impact and the feedback mechanism impact. Overall, Masset and Haddad (2014) conclude that the feedback mechanism can help enhance the knowledge and adoption impacts of FFS, but do not significantly influence yield outcomes.

The paper by Sanglestsawai *et al.* (2015) is a FFS impact evaluation study based on a cross-sectional dataset from onion farmers in the Philippines. The primary focus in this study was to comprehensively evaluate the effect of an IPM-centred FFS programme on a number of economic outcomes: yields, insecticide expenditures, labour expenditures, herbicide expenditures, fertilizer expenditures and profit. A PSM approach was used to deal with selection bias, and extensive testing was conducted to determine the potential effects of unobservable variable bias on the results. Results from Sanglestsawai *et al.* (2015) suggest that IPM-FFS participation statistically lowers insecticide expenditures, but does not statistically affect yields and other input expenditures. There is some evidence of a positive profit effect of IPM, but this result is not as strong as the insecticide expenditure effect (i.e. due to sensitivity of this result from potential bias due to unobservable variables). Given the weak evidence of a yield and profit effect of IPM-FFS, the authors indicate that farmers may lose motivation in using IPM practices promoted by these FFS programmes since there seems to be no strong evidence of a direct economic benefit to these producers.

Tsiboe *et al.* (2016) is the last study included in the present review, and it provides an evaluation of the impact of a cocoa-focused FFS aimed at improving livelihoods of small farmers in sub-Saharan Africa (Ghana, Cote d'Ivoire, Nigeria and Cameroon). The particular FFS programme evaluated in Tsiboe *et al.* (2016) was a comprehensive training approach that includes three components: topics on good agricultural practices (i.e. input application and access to high-yield cocoa varieties), business management and input credit access to farmers who complete the programme. A 2-year survey dataset was gathered before and after FFS implementation, and a DID analysis was used to assess the impact of FFS (and control for selection bias). Tsiboe *et al.* (2016) found that producers who participated in all three components of a 'full' FFS programme had a statistically significant improvement in their yields. However, there were no statistically significant yield effects observed for cocoa farmers who did not complete all three components of the programme (i.e. no yield effects for producers who only attended training for good agricultural practices and not the business/credit component). Tsiboe *et al.* (2016) also computed cost–benefit ratios for the FFS programme evaluated and results suggest that the programme is cost-effective (based on the estimated statistically significant yield effects for the full programme).

Economic Impact Evidence from Recent Studies

Given the brief description of each study included in this review above, we now summarize and estimate the average effects of FFS on several economic outcomes based on all these studies. For consistency, we calculate an average percentage change (relative to the 'base value' from control group) and report the number of studies that show a statistically significant effect. In calculating the average percentage change, there may be multiple impact estimates from each study (i.e. for example, if there are multiple estimation procedures used) that are averaged.

Yield effects

Based on the available yield impact estimates from the 2012–2016 studies reviewed in this article, the average yield impact of FFS is around 9.07% (see Table 3.3). Note that there is a mixture of positive and negative yield impact estimates reported, but the majority of the yield impacts of FFS was found to be statistically insignificant. This average percentage change is fairly close to the 13% estimate from the earlier Waddington *et al.* (2014) IPM-FFS review study.

Input use effects

Of the seven studies included in this review article, only the studies of Burger *et al.* (2015) and Sanglestsawai *et al.* (2015) explicitly investigate the effect of FFS on input use. Specifically, Burger *et al.*

Table 3.3. Estimated average percentage change in yields from reviewed 2012–2016 studies.

Study	% Change	Statistically significant? (10% level) yes/no	Remarks
Bonan and Pagani (2016)	11.87	No	From DD-PSM estimate (first comparison)
Bonan and Pagani (2016)	5.00	No	From DD-PSM estimate (second comparison)
Burger *et al*. (2015)	–0.07	No	Impact on rice yield
Burger *et al*. (2015)	11.23	Yes	Impact on tomato yield
Massett and Haddad (2015)	–11.52	No	Impact on rice yield (FFS with & without feedback vs control)
Massett and Haddad (2015)	0.57	No	Impact on cocoa yield (FFS with & without feedback vs control)
Massett and Haddad (2015)	–12.41	No	Impact on coconut yield (FFS with & without feedback vs control)
Massett and Haddad (2015)	–5.10	No	Impact on rice yield (FFS with feedback vs control)
Massett and Haddad (2015)	–5.09	No	Impact on cocoa yield (FFS with feedback vs control)
Massett and Haddad (2015)	–4.25	No	Impact on coconut yield (FFS with feedback vs control)
Sanglestsawai *et al*. (2015)	–43.59	No	Impact estimate onion yield (regression approach with IV)
Sanglestsawai *et al*. (2015)	18.89	No	Impact estimate onion yield (regression approach only)
Sanglestsawai *et al*. (2015)	13.42	No	Impact estimate onion yield (PSM kernel method)
Tsiboe *et al*. (2016)	32.00	Yes	Impact of full package FFS for cocoa in Ghana (% change as reported in article)
Tsiboe *et al*. (2016)	34.00	Yes	Impact of full package FFS for cocoa in Cote d'Ivoire (% change as reported in article)
Tsiboe *et al*. (2016)	50.00	Yes	Impact of full package FFS for cocoa in Nigeria (% change as reported in article)
Tsiboe *et al*. (2016)	62.00	Yes	Impact of full package FFS for cocoa in Cameroon (% change as reported in article)
Av. yield effect:	9.07		

% change calculated by dividing estimated impact by the base control group value (and multiplying by 100). FFS, Farmer Field School; DD-PSM, difference-in-differences with propensity score matching; IV, Instrumental variables.

(2015) examines the FFS impact on nitrogen (N) and potassium (K) fertilizer use, for both rice and tomato production; while Sanglestsawai *et al.* (2015) examines the impact of FFS on insecticide expenditures, labour expenditures, herbicide expenditures and fertilizer expenditures. But note that the FFS focus area in the Burger *et al.* (2015) study is on optimal fertilization practices, and the focus area in the Sanglestsawai *et al.* (2015) study is on promoting IPM practices. Therefore, the input effects from both studies are not really comparable and it does not make sense to aggregate the inputs that were examined in both studies (i.e. the fertilizer effects in both studies cannot be aggregated because of the difference in FFS focus areas).

With the focus on fertilizer use in the FFS evaluation by Burger *et al.* (2015), the average effect across all the estimates in their study is an increase in fertilizer use of around 20% (see Table 3.4). The effect is positive and significant especially for K fertilizer (both in rice and tomato), as well as N fertilization in tomato (but not in rice). One interesting fertilizer-related insight from Burger *et al.* (2015) is the statistically significant reduction in the 'distance' from the agronomist-determined 'optimal' fertilization rate for the FFS-treated farmers.

In Sanglestsawai *et al.* (2015), on the other hand, a statistically significant effect on insecticide expenditures was observed given the IPM focus of the FFS programme evaluated. The average insecticide expenditure impact across estimation methods was around 65% (see Table 3.4). This figure is well above the 39% insecticide reduction figure reported in Waddington *et al.* (2014). Note that the 65% magnitude reported here was pulled up by one large instrumental variable (IV) based regression

Table 3.4. Estimated average percentage change in input use from reviewed 2012–2016 studies.

Study	% Change	Statistically significant (10% level)? Yes/no	Remarks
Fertilizer-focused FFS:			
Burger *et al*. (2015)	2.87	No	FFS impact on N fertilizer for rice
Burger *et al*. (2015)	22.86	Yes	FFS impact on K fertilizer for rice
Burger *et al*. (2015)	25.35	Yes	FFS impact on N fertilizer for tomato
Burger *et al*. (2015)	27.71	Yes	FFS impact on K fertilizer tomato
Av. fertilizer effect:	19.70		
IPM-focused FFS:			
Sanglestsawai *et al*. (2015)	–37.45	Yes	FFS impact on insecticide expenditures (PSM kernel)
Sanglestsawai *et al*. (2015)	–37.86	Yes	FFS impact on insecticide expenditures (regression only)
Sanglestsawai *et al*. (2015)	–118.68	Yes	FFS impact on insecticide expenditures (regression with IV)
Av. insecticide exp. effect:	–64.67		

% change calculated by dividing estimated impact by the base control group value (and multiplying by 100). FFS, Farmer Field School; IPM, integrated pest management; IV, instrumental variable; PSM, propensity score matching.

estimate, which was consistent with an earlier study of Yorobe *et al.* (2011) conducted in the same study area (which also used an IV approach). The other estimates in Sanglestsawai *et al.* (2015) were around 37%, which is more in the ballpark of the Waddington *et al.* (2014) 39% estimate. All of the insecticide expenditure impact reported in Sanglestsawai (2015) was statistically significant. However, Sanglestsawai *et al.* (2015) did not find any statistically significant FFS impact on fertilizer, labour and herbicide expenditures.

Overall the input use impact results in Burger *et al.* (2015) and Sanglestsawai *et al.* (2015) suggest that FFS do tend to have a strong impact on the main ‘focus input’ of the FFS programme, but may not have a strong effect on the ‘non-focus’ inputs. There were relatively strong fertilizer use impacts in the fertilizer-focused FFS programme evaluated by Burger *et al.* (2015), and there were also strong insecticide reduction impacts in the IPM-focused FFS programme investigated by Sanglestsawai *et al.* (2015).

Effects on profits and/or income

Only the study by Sanglestsawai *et al.* (2015) provided any impact estimate of FFS on profits or income. When averaging all the profit impact estimates in Sanglestsawai *et al.* (2015), the average percentage increase in profit is around 28% (Table 3.5). However, note that half of the estimates were statistically insignificant and half were significant. In the article, Sanglestsawai *et al.* (2015) also noted that extensive testing on the effect of bias from unobservable variables may also eliminate the observed statistically significant estimates. Thus, they concluded that this profit impact result may not be reliable and without strong profit benefits of IPM it may be hard to promote (and diffuse) the IPM-recommended practices of the IPM-FFS programme.

Effects on adoption of FFS-recommended practices

The studies of Bonan and Pagani (2016) and Masset and Haddad (2015) are the only ones that provided any FFS impact estimate on adoption of the practices recommended and promoted by the programme. Based on parameter estimates from these two aforementioned studies, Table 3.6 shows that, on average, FFS increase the likelihood of uptake of the recommended practices by 32%. However, only three (of the seven) impact estimates averaged were statistically significant.

Table 3.5. Estimated average percentage change in profit from reviewed 2012–2016 studies.

Study	% Change	Statistically significant (10% level)? Yes/no	Remarks
Sanglestsawai *et al*. (2015)	39.14	Yes	FFS impact on profits (*t*-test on unmatched sample)
Sanglestsawai *et al*. (2015)	38.60	Yes	FFS impact on profits (PSM 1-to-1)
Sanglestsawai *et al*. (2015)	31.89	No	FFS impact on profits (PSM 10-to-1)
Sanglestsawai *et al*. (2015)	34.47	No	FFS impact on profits (PSM kernel)
Sanglestsawai *et al*. (2015)	43.00	Yes	FFS impact on profits (regression only)
Sanglestsawai *et al*. (2015)	–17.27	No	FFS impact on profits (regression with IV)
Av. profit effect:	28.30		

% change calculated by dividing estimated impact by the base control group value (and multiplying by 100). FFS, Farmer Field School; IV, instrumental variable; PSM, propensity score matching.

Table 3.6. Estimated average percentage change in the probability of adoption of FFS-recommended practices from the reviewed 2012–2016 studies.

Study	% Change	Statistically significant (10% level)? Yes/no	Remarks
Bonan and Pagani (2016)	102.50	No	JFFS impact on adoption of recommended practice 1 (DID PSM estimate)
Bonan and Pagani (2016)	152.94	Yes	JFFS impact on adoption of recommended practice 2 (DID PSM estimate)
Bonan and Pagani (2016)	–62.50	No	JFFS impact on adoption of recommended practice 3 (DID PSM estimate)
Bonan and Pagani (2016)	–21.32	No	JFFS impact on adoption of recommended practice 4 (DID PSM estimate)
Masset and Haddad (2015)	4.51	No	Full FFS impact on adoption of recommended rice practices
Masset and Haddad (2015)	35.86	Yes	Full FFS impact on adoption of recommended cocoa practices
Masset and Haddad (2015)	13.42	Yes	Full FFS impact on adoption of recommended coconut practices
Av. adoption effect:	32.20		

% change calculated by dividing estimated impact by the base control group value (and multiplying by 100). DID, difference-in-differences; JFFS, Junior Farmer Field School; PSM, propensity score matching.

Effects on knowledge

Based on the 2012–2016 FFS studies included in the present article, the studies of Bonan and Pagani (2016), Guo *et al*. (2015) and Masset and Haddad (2015) provided clear FFS impact estimates on agricultural knowledge. On average, results from these studies suggest that FFS increases knowledge scores by about 72% (Table 3.7). The majority of the impact estimates were also statistically significant. These results suggest that the FFS approach tend to be effective in facilitating the learning process of participating FFS producers. The study of Guo *et al*. (2015) also provided evidence that the fertilizer-focused FFS they evaluated statistically improved Chinese rice farmers' pest-management-related knowledge and knowledge about agri-environmental issues. However, the Burger *et al*. (2015) study, which is the larger project that Guo *et al*. (2015) is a sub-project on, suggest that FFS did not have a strong impact on Chinese tomato farmers' knowledge. Overall, the strong positive impact of FFS on knowledge observed in the studies above is consistent with some of the earlier impact studies on FFS (Waddington *et al*., 2014).

Table 3.7. Estimated average percentage change in overall knowledge scores from the reviewed 2012–2016 studies.

Study	% Change	Statistically significant (10% level)? Yes/no	Remarks
Bonan and Pagani (2016)	345.83	No	JFFS impact on overall knowledge score (DID PSM)
Guo *et al*. (2015)	7.58	Yes	FFS impact on average knowledge score across topics (DID, no interactions)
Guo *et al*. (2015)	25.14	Yes	FFS impact on average knowledge score across topics (DID, with interactions)
Masset and Haddad (2015)	8.04	No	FFS impact on overall knowledge score for rice practices
Masset and Haddad (2015)	35.86	Yes	FFS impact on overall knowledge score for cocoa practices
Masset and Haddad (2015)	7.19	Yes	FFS impact on overall knowledge score for coconut practices
Av. knowledge effect:	71.61		

% change calculated by dividing estimated impact by the base control group value (and multiplying by 100). DID, difference-in-differences; JFFS, Junior Farmer Field School; PSM, propensity score matching.

Effects on other outcomes: spillovers, food security and poverty

Bonan and Pagani (2016) and Burger *et al.* (2015) are the only two 2012–2016 studies in this review that explored the spillover effects of FFS. Bonan and Pagani (2016), given its focus on a JFFS programme, only looked at the limited spillover effect from the junior students to members of their own households (i.e. their parents primarily). On the other hand, Burger *et al.* (2015) examined the potential spillover effect from farmers who attended the FFS to farmers who did not attend FFS but are in the same village as the FFS attendees. Results from Bonan and Pagani (2016) indicate that there are some spillover effects from the junior student to other household members, especially with regard to agricultural knowledge. In contrast, the findings of Burger *et al.* (2015) indicate that there is no strong positive spillover effects from treated to untreated farmers within villages (both for rice and tomato producers).

The studies of Bonan and Pagani (2016) and Larsen and Lilleor (2014) provided some analysis on the effects of FFS on nutrition and/or food security. Due to the number and variety of 'nutrition outcomes' utilized in both studies, it is difficult to provide a sensible approach for averaging all impact estimates. As such, we only report the general food security results in these two studies. Results from both Bonan and Pagani (2016) and Larsen and Lilleor (2014) reveal that FFS do tend to have a positive effect on the FFS-attending household's food security and nutrition. Not all FFS impacts on nutrition-related outcomes have strong statistical effects, but a fair amount do. Hence, we can say that the livelihood-focused FFS investigated by Bonan and Pagani (2016) and Larsen and Lilleor (2014) have provided some discernible nutrition-related impacts.

In terms of poverty effects, only the study of Larsen and Lilleor (2014) has examined the FFS impact on this specific poverty outcome. However, they did not find any strong statistical evidence that FFS affect the poverty status of the participants.

Conclusions and Implications

This study reviews literature from 2012–2016 that evaluated the impact of the FFS approach on a number of production-related and/or household-related economic outcomes for a variety of countries. The aim is to 'build on' a recent review by Waddington *et al.* (2014) that analysed past studies (i.e. pre-2012) which evaluate the impact of different IPM-FFS programmes worldwide. Although the studies examined in this article also include 'non-IPM-focused' FFS programmes, most of the studies reviewed also examine the impact of FFS on similar economic outcomes as 'IPM-focused' programmes.

Thus, lessons can still be learnt from the more recent FFS impact studies that are both IPM- and non-IPM-focused.

Overall, results from the current review are fairly consistent with the aforementioned Waddington *et al.* (2014) study. The recent studies reviewed, which are considered to have a 'medium' to 'low' risk of bias, tend to show statistical evidence of positive FFS impacts on: (i) FFS-targeted inputs (e.g. improved fertilizer use for fertilizer-focused FFS, and reduced pesticide use for IPM-focused FFS); (ii) participant knowledge about the agricultural topics being promoted; and (iii) the adoption/uptake of the practices being promoted by the FFS. There is also evidence of positive food security impacts for livelihood-focused FFS. However, there seem to be limited (or at least weaker) impacts of FFS on yields, profits, spillovers to other non-FFS farmers and poverty measures. Note that in the Waddington *et al.* (2014) review, the strongest impact of FFS was seen for input use as well, with more moderate effects on yields, profits and spillovers to other non-FFS farmers. However, most of these recent impact results are only based on more 'short-run' outcomes, largely from 1- to 2-year datasets (i.e. baseline and follow-up survey data).

The 2012–2016 studies reviewed point to several new insights that have important implications for improving the FFS approach and for further research on its effectiveness. First, following one major recommendation from Waddington *et al.* (2014), there are now a couple of FFS impact evaluations where a RCT approach was used, which is considered to have 'low risk of bias' because of the randomization of FFS treatment (i.e. thus, there is no selection bias). Burger *et al.* (2015), Guo *et al.* (2015) and Masset and Haddad (2015) all utilize a RCT approach to assess the economic impacts of FFS. An important (and reassuring) result from these 'low risk of bias' studies is that inferences from these studies are still fairly consistent with other studies that used quasi-experimental statistical approaches (i.e. methods that control for bias through non-randomization statistical techniques) and are considered by Waddington *et al.* (2014) as studies with a 'medium risk of bias'.

Second, a number of the more recent FFS impact studies also indicate scepticism about the effectiveness of scaling up the traditional FFS approach due to weak evidence about the yield and profit impacts of this approach. Sanglestsawai *et al.* (2015), for example, suggest that without direct economic benefits (i.e. profit impacts) of FFS (and the associated FFS-recommended practices) it may be hard to justify further scaling up of this approach. Given that most of the studies only indicate weak evidence of IPM-FFS participants having statistically higher yields or profit (vis-à-vis non-IPM-FFS participants), it could be that the cause of this lack of impact is due to (i) the IPM practice itself not generating net economic benefits (i.e. which presumes that IPM-FFS participants generally adopt the practice), or (ii) the FFS approach itself was not successful in imparting the appropriate knowledge to implement the IPM tactics (i.e. the IPM tactics recommended have been proven to show profitability except that they were not adopted or implemented properly). Or perhaps it is a combination of (i) and (ii). If the lack of profit impact is due to (i), then this finding implies that entomologists and scientists developing IPM techniques may need to evaluate overall profit effects of these IPM methods (and/or combination of methods) in their medium- to long-term on-farm trials, in addition to the effectiveness of these methods for controlling the target pests. Agricultural economists and entomologists (and/or other scientists) working together in inter-disciplinary teams to evaluate profit and cost effects of these IPM techniques may be critical in its promotion and diffusion (regardless of whether an IPM-FFS approach or other extension approach is used as the educational vehicle). If the likely cause of the weak profit impact of IPM-FFS is (ii) above, then scientists and the FFS trainers/facilitators may need to collaborate to determine how to better approach the dissemination of IPM knowledge within the FFS framework. One consideration in improving how IPM knowledge is imparted is the additional cost involved to do this in a FFS framework. Other IPM information dissemination approaches (other than through FFS), and the associated costs for these alternative approaches, would also need to be studied (more on this in the last paragraph). There may be more cost-effective informational approaches that can diffuse proven profit-generating IPM knowledge.

Third, an important new issue raised from the recent literature is with respect to heterogeneity of impacts. Most of the studies that evaluated FFS only looked at the mean or average impact of FFS (where average yield and profit results were not impressive). But it could be that there are subpopulations of farmers with certain characteristics that directly benefit from this approach (see Burger *et al.*, 2015). Hence, future studies should focus on this heterogeneity issue to give more precise insights as to what type of farmer benefits (or not) from an FFS approach. These types of studies can help in further streamlining and targeting FFS for enhanced effectiveness. Moreover, this heterogeneity issue has important implications for entomologists, economists and scientists involved in developing and evaluating the overall effectiveness of IPM methods and IPM-FFS programmes. For example, as Head and Savinelli (2008) have already pointed out, IPM methods being developed by scientists should be properly tailored for the local conditions (i.e. physical, social and/or environmental) and needs of target farmers. Understanding when and where particular IPM techniques (and IPM-FFS programmes) are successful (or not) can inform further tailoring of IPM methods and IPM-FFS programmes so that they can be made profitable for a variety of conditions and types of farmers. Specifically, IPM-FFS programmes may also further emphasize the need for understanding the environmental 'designs' (or conditions) for which certain IPM control practices are profitable or not, and incorporate this into multi-year IPM-FFS programmes.

A related issue to heterogeneity is exploring effects of FFS on other 'non-traditional' economic outcomes. Larson and Lilleor (2014) provide a step in the right direction where they try to examine FFS effects on nutrition and poverty. Further studies in this vein are still needed – for example, IPM-FFS impacts on farmer health and the environment.

Lastly, as noted above, many of the FFS impact studies only examine 'short-run' to 'intermediate-run' economic outcomes. Arguably, there may be 'longer-run' economic impacts of FFS that manifest over several years. Further research is needed to examine the longer-run effects of FFS and whether the intermediate outcome results are sustained through the years (i.e. perhaps a long-run RCT on IPM-focused FFS). Rejesus *et al.* (2012), for example, show that intermediate knowledge gains and insecticide reduction from IPM-FFS are not sustained over time. This may be related to the seemingly small (or no) yield and/or profit effects observed in previous economic studies of IPM-FFS (i.e. perhaps over the medium- to long run, farmers notice that lack of economic benefits) and also other factors that influence farmer behaviour over time (e.g. promotional activities of chemical companies). Related to the heterogeneity discussion above, a long-term perspective in evaluating IPM methods and IPM-FFS programmes is needed to gain insights into what 'design' factors contribute to sustained economic effectiveness of particular IPM procedures.

Assessing longer-term results (and behavioural changes over time) also has important implications for more accurate cost–benefit calculations of the FFS approach. On this note, further research that more carefully examines the cost-effectiveness of FFS over longer periods of time would also be beneficial to extension policy makers when deciding on whether to scale up these FFS programmes to the national level or to consider other information dissemination approaches for particular practices (e.g. the 'No Early Spray' mass media campaign in Vietnam that promotes pesticide reduction through radio and TV spots; Rejesus *et al.*, 2009).

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4 Economic Value of Arthropod Biological Control

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

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

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

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

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

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

Concepts and Methods

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

Measuring farm-level impacts

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

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

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

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

Measuring market-level impacts

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

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

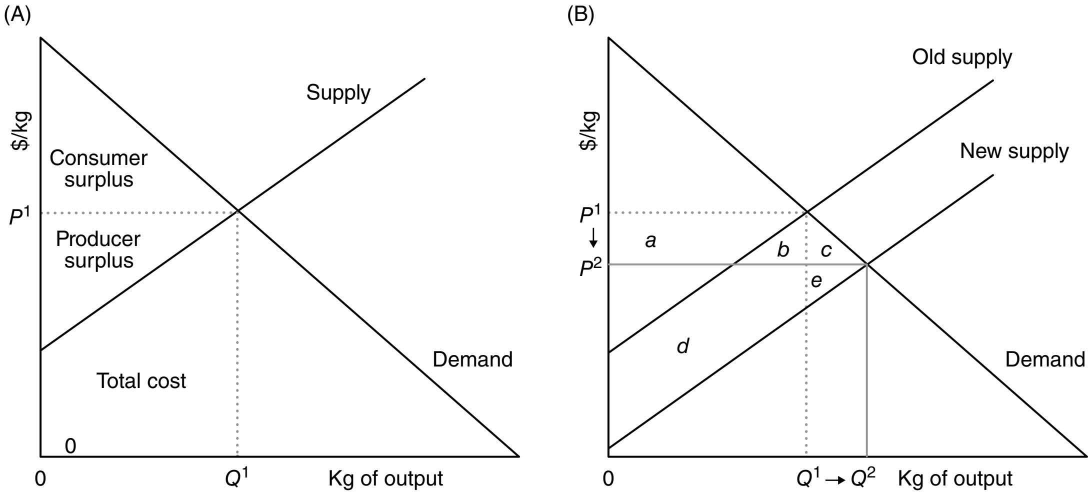

Fig. 4.1. (A) A general economic surplus model defining consumer, producer, and total cost. (B) The addition of successful biological control shifts the supply curve to the right. Consumer surplus increases by the sum of *a* + *b* + *c* because they can purchase more of the good, and at a lower price.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

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

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

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

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

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

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

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

Benefit–cost analysis

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

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

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

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

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

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

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

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

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

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

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

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

Externalities – non-market benefits and costs

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

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

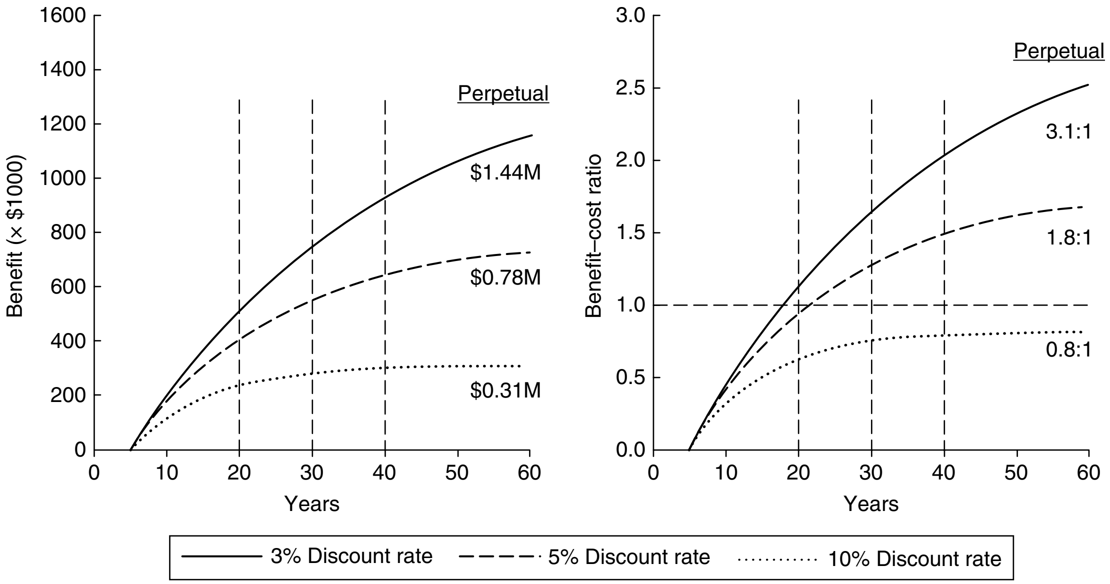

Fig. 4.2. Hypothetical case in which the benefits are $50,000 annually after the fifth year and the cost of the programme is $100,000 annually for the first 5 years. The example shows how the discount rate of money and the time horizon used to estimate benefits affect the outcome in terms of benefit–cost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

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

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

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

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

Introductory (Classical) Biological Control

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

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

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

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

Continued

Table 4.1. Continued.

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

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

Continued

Table 4.1. Continued.

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

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

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[a] All figures in 2018 constant US$ (gross domestic product: implicit price deflator, http://research.stlouisfed.org/fred2/series/GDPDEF/); data prior to 1947 were converted using the implicit price deflator for 1947.

[b] Currencies converted to US$ using https://data.oecd.org/conversion/exchange-rates.htm#indicator-chart; conversions prior to 1950 used conversion factor for 1950.

[c] Discount rates and horizon years were standardized to 10% and 30 years where possible using data provided by study authors; original study rates and years indicated in parentheses. N/A = not applicable.

[d] Cock *et al.*, 2016; N/A = not available in database.

[e] Noted as C by Huffaker *et al.*, 1976, but no control in the BIOCAT database.

*27 different countries in Africa.

†PB – partial budgeting; CV – contingent valuation; ESM – economic surplus model.

‡P – partial control; C – complete control; S – substantial control.

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

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

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

The record of evaluations

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

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

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

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

Economic approaches and outcomes

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

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

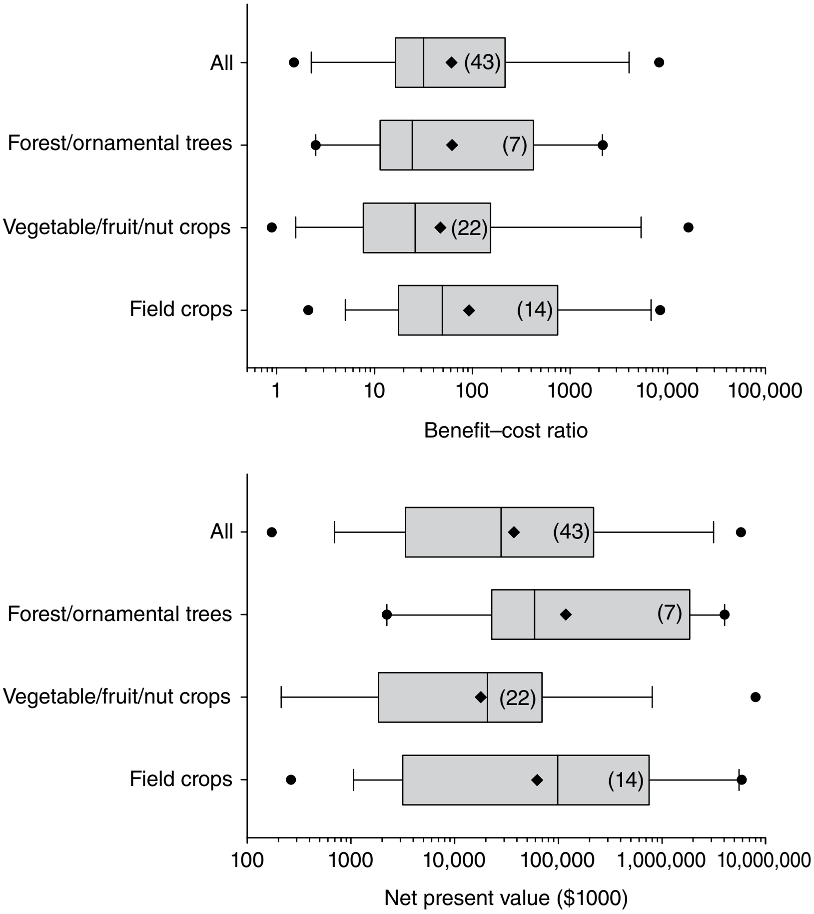

Fig. 4.3. Summary of benefit–cost ratios and net present values (NPV) for introductory biological control projects from 1930–2013. For box plots, the line within each box represents the median, the box bounds the 25th and 75th percentiles, the whiskers denote the 10th and 90th percentiles, round points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

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

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

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

Augmentative Biological Control

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

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

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

Conservation Biological Control

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

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

The record of evaluations

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

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

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

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

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

Continued

Table 4.2. Continued.

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

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

Continued

Table 4.2. Continued.

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

[a] All figures in 2018 constant US$ (gross domestic product: implicit price deflator, http://research.stlouisfed.org/fred2/series/GDPDEF).

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

Economic approaches and outcomes

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

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

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

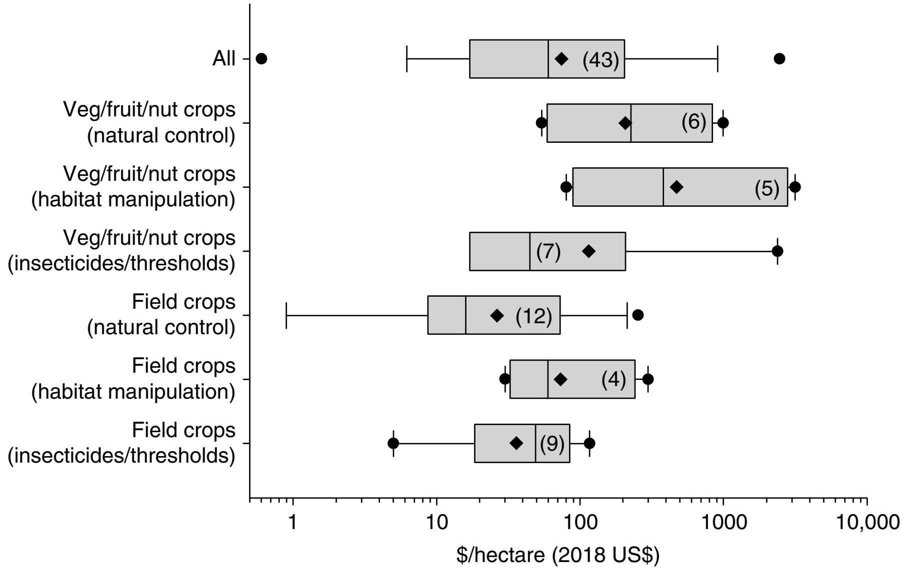

Fig. 4.4. Summary of economic valuations for conservation biological control and natural control of arthropod pests relative to crop type and approach to conservation. Insecticides/thresholds involve studies using selective insecticides and/or biological control based thresholds. Habitat manipulation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

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

Modified insecticide use and economic thresholds

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

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

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

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

Habitat manipulation

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

Considerations for Moving Forward

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

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

Constraints to uptake of biological control

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

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

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

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

Hard technology, advantage and challenge to biological control

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

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

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

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

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5 Economics of Host-Plant Resistance

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Host-plant resistance (HPR) has been declared the foundation of integrated pest management (IPM), which is compatible with all strategies and integrated tactics (Wiseman, 1985). Luginbill (1969) described HPR as 'the ideal method of controlling insects'. Wiseman and Webster (1999, p. 1) called HPR 'one of the most ideal pest management strategies for field crops'. Gu *et al.* (2008, p. 1543) declared 'the use of pest resistant crop has become an essential tactic in an IPM system'. Naranjo *et al.* (2008) described HPR as one of the foundations of IPM. Yet, as Wiseman and Webster (1999, p. 1) have stated, 'in recent years we have not done a very good job of informing the public about the value of insect-resistant field crop varieties'. Wiseman and Webster claimed that relevant economic data are difficult or expensive to obtain.

An example of benefits of HPR greatly exceeding the original costs is the development of grape (*Vitus vinifera*) resistant to *Daktulosphaira vitifoliae*, grape phylloxera, a root-injuring pest. Although this case does not involve seed, it still is a worthwhile story. In 1870, Charles V. Riley, J.E. Planchon and T.V. Munson found a solution to the devastation caused by this pest to the French wine industry, which had been growing *V. vinifera* grape varieties (Smith, 1992). *Vitis vinifera* scions were grafted onto the roots of a resistant *Vitis aestivalis* or other American native species. This gave the grape protection but kept most of the valuable characteristics of the European grape. American rootstock has been deployed worldwide to protect the grape industry since then. However, some rootstocks are not as good as others. A rootstock called AxR1 has one parent that is a *V. vinifera* variety. The resistance provided by this rootstock had failed in many parts of the world by the early 20th century. Grape phylloxera initially did not cause much damage to AxR1 roots, but within 20 years, mutation and natural selection within the grape phylloxera population began to overcome this rootstock, resulting in the eventual failure of most vineyards planted on AxR1. Walker *et al.* (2014) provide an update to this story of rootstock-based HPR.

As the foundation of system designs for IPM in crop production, it is easy to take HPR for granted. Often the crop varieties that are planted today are the products of hundreds or thousands of years of incremental development. Or the success of plant resistance is based on academic or governmental research that either has been forgotten or rarely quantified in cost. Perhaps the benefits are so obvious for commercial seed with resistance that it is not worth bothering to calculate the costs.

To fully justify and evaluate HPR we need to better understand the cost of research and development for resistant crops. If the HPR was developed entirely by the private sector, then the new higher price for seed usually accounts for that research and development. However, for contributions from the public sector, it is difficult to determine the cost. Even books dedicated to HPR do not discuss its costs (Painter, 1951; Maxwell and Jennings, 1980; Hedin, 1983; Smith, 1989, 2005; Panda and Khush, 1995). Perhaps this is due to the difficulty of separating crop protection components from general improvements in plant germplasm. Was a stronger stem developed for mechanical harvesting or for resistance to pests? Was the crop maturation period changed in a breeding programme to avoid

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pests or to make other aspects of management more efficient? Society and government leaders need to know what benefit is being derived from investments in plant breeding in government agencies and university labs. The costs and benefits can then be compared. Because farmers may be using seed subsidized by the public sector with 'free' resistance added to germplasm, they may usually consider HPR to be worthwhile.

One aspect that we must not forget is the bias in publications about HPR. Most published studies highlight positive results with research and development. Very few crop varieties reach field trials unless they show harvestable yields similar to those of older varieties. And then the value of a variety, that may yield more under high pest pressure because of resistance to pests, still must be shown to be economical in most situations faced by farmers (Kaplan *et al*., 2009). Otherwise, farmers will prefer higher yields in most years with older crop varieties with protection provided by some other IPM tactic in the years with high pest pressure. Thus, a survey of publications will likely not cover the costs of failures and limited successes, leading to biased views in favour of HPR.

Native Traits

In this section, we highlight several crops that have a long history of breeding programmes that have improved resistance to insect pests (Dhaliwal *et al*., 2005). The set is further restricted to those with some effort to evaluate the economics of HPR. By native traits, we mean traits found in the same plant species or close relative and developed in a traditional breeding programme involving introgression of donor genetics into elite and productive cultivars.

Alfalfa (*Medicago sativa*) is a perennial crop harvested more than once per year for its stems and leaves, which are fed to livestock. Ward *et al*. (1990) determined that improved cultivars of alfalfa produced 20% greater returns per ha over the last 5 years of a 6-year harvesting period for this perennial crop compared with the traditional cultivar. The traditional cultivar was failing in the final year. Thus, resistant cultivars increased stand longevity beyond the typical 3 years. Note that the new cultivars may have had more than just resistance to insects or increased longevity. But Ward *et al*. (1990) did not account for cost of developing the improved cultivars. Dellinger *et al*. (2006) performed a farm-based economic analysis of one alfalfa cultivar resistant to *Empoasca fabae* and one traditional alfalfa cultivar, both of which were commercially available. They found that a grower in the United States would earn more net revenue by planting the traditional, susceptible cultivar, because of the price premium for the resistant seed and the need to treat the new cultivar with insecticides to control both *E. fabae* and *Hypera postica*. This is a rare case of a failure of HPR being published.

Before insecticidal transgenic cotton was developed, the most important resistance trait developed for conventional cotton (*Gossypium hirsutum*) and introduced after 1978 in the United States was likely the one that shortened the growing season by 2–3 weeks (Jenkins, 1999). The shorter growing period reduced exposure of the crop to insect damage. No estimate of the cost of developing this trait has been published.

Salkin *et al*. (1976) calculated that greenbug (*Schizaphis graminum*) resistant hybrids of sorghum (*Sorghum bicolor*) produced net returns per ha 1.4–12% greater than conventional insecticides in Oklahoma. These calculations included the higher cost of producing the new sorghum seed, which plant breeders estimated to be 25% more given the difficulties in pollinating resistant sorghum.

Eddleman *et al*. (1999) provide a detailed analysis of the value to society and farmers of public investment in HPR. Over an 11-year period, ten germplasm lines of sorghum resistant to one biotype of greenbug were developed at three universities. Eddleman *et al*. (1999) evaluated the consumer surplus and producer surplus derived from this investment and use of resistant sorghum. The net benefit to society is the sum of the two surpluses. Total investment in the research and development program was $8.54 million. They assumed that research would continue after the 11th year at 80% of previous funding to maintain value in the resistant germplasm until year 20. Using field data for sorghum yield differences and costs of alternative insect control from 1987–1989, Eddleman *et al*. determined that this HPR programme earned a 33–48% return per year. According to Eddleman *et al*., these returns on public investment are similar to rates determined in other studies of a variety of production-oriented, agricultural research.

Genetic resistance in wheat (*Triticum aestivum*) is the most efficacious method for control of *Mayetiola destructor* (Hessian fly) in the United

States (Cambron *et al.*, 2010). Over 30 native traits for resistance to *M. destructor* have been developed in wheat cultivars over many decades of research. Because these traits have been deployed as single genes (not as pyramids of multiple genes) in commercial cultivars of wheat, biotypes or strains of virulent (resistant) *M. destructor* have evolved within 6–8 years to overcome the benefits of HPR (Schmid *et al.*, 2018). For example, when over 20 of these traits were tested in the southern United States, more than half failed to prevent damage because of the existence of resistant insects (Cambron *et al.*, 2010). Accounting for HPR in wheat is even more complicated because breeding programmes do not always identify resistance to this pest (Schmid *et al.*, 2018); therefore, it is often not known which if any resistance traits exist in commercial wheat cultivars. Furthermore, some resistance traits are only effective below 20°C (Schmid *et al.*, 2018). Smiley *et al.* (2004) demonstrated that resistant wheat cultivars had much higher grain yields than susceptible cultivars in Oregon, but they did not account for the social cost of the HPR. Azzam *et al.* (1997) determined the social benefits of the $1.8 million investment in research to develop wheat varieties in Morocco resistant to *M. destructor*. They concluded that the internal rate of return for this programme was at least 39% for the 10 years of expected durability of the traits. The benefit–cost ratio for Morocco for the 27 lines of wheat was expected to be 9:1 according to Azzam *et al.* (1997).

Widawsky *et al.* (1998) described the adoption of HPR for rice (*Oryza sativa*) production in China and investigated the economics of HPR relative to insecticide use. Although several rice varieties with native traits for HPR were grown in China, their use rarely reduced the application of insecticides. Based on their economic analysis, they concluded that economic returns to improving HPR against insects may be substantial. Widawsky *et al.* (1998) described the value of HPR to Chinese rice production (for two provinces) using production elasticities. With only a 1% increase in HPR, rice production would increase by $281,000 to $1.49 million. The authors caution that the calculations do not take into account changes in the overall market due to a larger supply of rice. However, Widawsky *et al.* (1998) concluded that these benefits are large compared with the ~$1.5 million per year that was spent on all rice research in four provinces in eastern China.

Transgenic Insecticidal Crops

Because of the biotechnology and typical need for regulatory approvals, it costs ~$136 million and ~13 years to commercialize a transgenic insecticidal crop variety (McDougall, 2011; Prado *et al.*, 2014). These types of investments are usually only made by large companies developing seed for large markets, particularly those for field crops. However, efforts have been made to introduce transgenic insecticidal traits into vegetables with smaller markets (Shelton, 2012).

One of the few examples of the use of transgenic insecticidal traits in a commercial vegetable is Bt brinjal (*Solanum melongena*) in Bangladesh (Prodhan *et al.*, 2018). This vegetable is commonly grown throughout Asia where it is attacked by the Lepidopteran, *Leucinodes orbonalis*. Yield losses in Bangladesh are very high and farmers rely on extensive and frequent insecticide applications to reduce injury. Concern for both human health and the economics of production led to the development of this transgenic insecticidal vegetable through a collaboration of several agencies. The Maharashtra Hybrid Seed Company (Mahyco) in India performed the early work by inserting the insecticidal *Cry1Ac* gene from the bacterium *Bacillus thuringiensis* (Bt) into *Solanum melongena*. Then a partnership was formed between Mahyco and public sector partners in India, Bangladesh, the United States and the Philippines (Hautea *et al.*, 2016; Shelton *et al.*, 2018). Mahyco donated the specific genetic event to the Bangladesh Agricultural Research Institute, which incorporated it into local *Solanum melongena* varieties (Shelton *et al.*, 2018). By 2018, 17% of *Solanum melongena* farmers in Bangladesh had adopted the Bt brinjal varieties (Shelton *et al.*, 2018). In an economic study before the commercial release of Bt brinjal, Islam and Norton (2007) predicted that Bt brinjal in Bangladesh would decrease insecticide use by 70–90%, increase yield by 15–30% and increase the value of the crop by 37–64%.

Prodhan *et al.* (2018) evaluated the economics of four Bt brinjal varieties commercialized in Bangladesh. They compared these to their non-Bt isolines, produced with and without the standard series of insecticide applications, in field trials. Prodhan *et al.* (2018) used a partial-budgeting analysis to estimate profits (price × *Solanum melongena* yield – variable costs) for each treatment. The variable cost of production was $2258/ha for sprayed plots and $1139/ha for non-sprayed plots. In both years, all Bt varieties produced higher profits than their isolines, regardless of whether they were sprayed or not. In 2016, all four Bt brinjal varieties were profitable, even when no sprays were applied. But only two of the non-Bt isolines that were sprayed were profitable when sprayed and only one of the unsprayed non-Bt isolines produced a profit. In 2017, all of the non-sprayed, non-Bt isolines lost money, as did one of the unsprayed Bt brinjal varieties.

In another study conducted by scientists at the Bangladesh Agricultural Research Institute during the 2016/17 cropping season (Shelton *et al.*, 2018), net returns were $2151/ha for Bt brinjal compared with $357/ha for non-Bt brinjal. This study also indicated that farmers growing Bt brinjal saved 61% of the pesticide cost compared with farmers growing non-Bt brinjal (Shelton *et al.*, 2018). In the two field research studies (Prodhan *et al.*, 2018; Shelton *et al.*, 2018), the Bt and non-Bt seed had the same cost because they were provided for free.

One of the first Bt crops commercialized for markets for produce directly consumed by humans was Bt sweetcorn (*Zea mays*, convar. *saccharata*). Speese *et al.* (2005) studied sweetcorn production in Virginia, USA. They first determined that it is not profitable to grow fresh-market sweetcorn without adequate insect pest management. Speese *et al.* (2005) observed much less insect damage on the Bt sweetcorn than on the non-Bt isolines that were not sprayed or sprayed with insecticides up to six times per season. Based on a comparison between insecticide-treated non-Bt sweetcorn and Bt sweetcorn, Speese *et al.* concluded that growers would gain $547/ha by growing Bt sweetcorn. If Bt sweetcorn were sprayed twice with an insecticide, this gain would be ~$1777/ha. In their study, the cost of Bt maize seed was almost double the price of traditional seed.

The price of transgenic seed depends on the costs of development and the competitiveness of the market (NRC, 2010). Transgenic insecticidal crop seed for field crops almost always has an obvious price that is higher than that of seed without the new trait, a price premium or technology fee (NRC, 2010). From 2000–2007, the seed price index for transgenic maize, soybean and cotton in the United States exceeded the average index of prices paid by US farmers for inputs by 30% (NRC, 2010). The inflation-adjusted price of transgenic maize seed increased ~40% from 1994–2009, while higher rates of increase were recorded for soybean and cotton (NRC, 2010). Naranjo *et al.* (2008) and Qaim *et al.* (2008) provided details about the variability in the seed premiums for transgenic insecticidal traits, compared these to the profits made by farmers in various countries and concluded that often the benefits exceed the costs. Qaim *et al.* (2008) reported that, in publications since 2000, seed premiums in various countries have ranged from $10–40/ha for Bt maize and from $23–87/ha for Bt cotton (Qaim *et al.*, 2008). From 1996–2005, Naranjo *et al.* (2008) reported that premiums for Bt cotton seed ranged from $40–250/ha with most cases below $68/ha. (It would be interesting to know if native traits for HPR increase the social, if not farmer's, cost of seed by similar amounts.)

Given that the farmer's cost is easy to determine from the price premium applied to privately developed transgenic seeds (NRC, 2010), the short-term, economic value to farmers of the new HPR can be evaluated directly in field studies similar to those for any HPR (Baute *et al.*, 2002). A field experiment can determine the protection afforded by the insecticidal trait and any negative aspects, such as yield drag, which could produce lower average yields in insecticidal crops when pest densities are low.

However, because of the typically high efficacy of transgenic insecticidal traits in reducing pest populations, two major complications exist when performing economic analyses. The first aspect that differs from the deployment of native traits is the requirement in several countries that non-insecticidal crop seed also be planted as a refuge for susceptible insects to delay the evolution of resistance (Hurley and Mitchell, 2014). These countries include Canada, South Africa, the United States, Argentina and the Philippines. Often there are restrictions on how these refuges must be managed and protected; therefore, the costs and benefits of refuge must also be considered. For example, when the US Environmental Protection Agency eliminated the 5–20% on-farm refuge requirement for Bt cotton growers in the southern US and permitted them to rely on natural refuges of wild host plants or refuges provided by other non-Bt crops, the benefits of the refuge change for Bt cotton growers were estimated for North Carolina to be $66 per year per affected ha (Piggott and Marra, 2007).

The second major complication in economic analyses of transgenic insecticidal crops is the need to account for long-term costs and benefits as the efficacy of the HPR caused by these traits declines due to evolution of pest resistance (Onstad and Knolhoff, 2014). Usually, the commercialized insecticidal traits kill a very high proportion of the targeted pests feeding on them. Furthermore, these very high rates of mortality are constant throughout most of the crop's seasonal development. In other words, the HPR in these cases is highly effective, which is good in the short term for farmers, but bad in the long term because of evolution of resistance. Hence, many economic evaluations of transgenic insecticidal crops consider time horizons of at least 10 years to account for declining value of the traits but also the long-term value of the refuges. This does not mean that farmers have the same time horizons for management decisions. But a long-term view may be realistic because transgenic insecticidal traits are expensive and developed slowly, and industry and regulators both prefer longer time horizons.

To predict the consequences of deploying transgenic insecticidal traits, mathematical modelling and simulation of decades of pest population dynamics and genetics are needed to evaluate the long-term, future economics of strategic choices. In these modelling studies performed before commercialization of HPR, the modelling is used to decide which way to integrate HPR with other tactics, how much and which type of refuge to recommend or require, and how to deploy multiple insecticidal traits (sequentially or as a combination of two traits targeting the same pest).

Onstad and Guse (1999) simulated the population dynamics and genetics of *Ostrinia nubilalis* and its damage to maize in a hypothetical region of the United States containing Bt maize and refuges of non-Bt maize planted at constant proportional areas over 15–20 years. They used modelling to find the dominant or superior level of refuge based on minimization of the net present value of overall cost (yield losses and extra seed costs) in the simulations. Based on the results, Onstad and Guse (1999) predicted that Bt maize would significantly lower damage to maize in the refuges. For most scenarios without toxin-titre decline during maize senescence, a 20% refuge is a robust, efficient choice. At extremes of initial pest density or crop value (price × expected yield), refuge levels as low as 8% or as high as 26% can be superior. Non-Bt maize could be planted as strips (at least six rows per strip) within a field or as separate but adjacent blocks to be effective at delaying resistance and providing economic returns at a 20% refuge level. If the HPR was weakened by toxin-titre decline during senescence, a 10% refuge level provided a robust, efficient solution for farmers. Hurley *et al.* (1997) concluded that optimal strategies even better than those with constant refuge levels would probably involve reducing use of Bt maize after regional pest populations are decimated.

Eleven years after the work of Onstad and Guse (1999), Hutchison *et al.* (2010) measured real costs and benefits of the same system which started with a 20% required refuge for single-trait Bt maize. Hutchison *et al.* (2010) concluded that the cumulative benefits over the first 14 years of commercial planting were $3.2 billion for maize growers in Illinois, Minnesota and Wisconsin, with more than $2.4 billion of this total accruing to non-Bt maize growers. Similar estimates for Iowa and Nebraska were $3.6 billion in total, with $1.9 billion for non-Bt maize growers (Hutchison *et al.*, 2010). In this field maize system, non-Bt fields provide the refuges for susceptible *O. nubilalis* to delay the evolution of resistance due to the strong selection pressure in the Bt maize fields. Hutchison *et al.* (2010) demonstrated the value of maintaining refuges to protect HPR and the overall value of Bt maize, supporting the conclusions of Onstad and Guse (1999).

If entomologists simply use biology to guide their recommendations, they may propose unrealistically high refuge levels, because evolution of pest resistance can be delayed a very long time by making refuges as close to 100% as possible. However, farmers want to grow crops with HPR and society wants to consume reasonable amounts of harvested produce at reasonable prices. When economics is considered, refuge levels between 5 and 30% are often shown to be efficient. For example, Onstad *et al.* (2014) simulated a bio-economic model of *Diabrotica virgifera virgifera* over a 15-year period beginning after significant adoption of the Bt maize. The primary focus of their analysis was the economic evaluation (net present value of grower profit) of Bt maize and its refuge planted continuously year after year (continuous maize). Onstad *et al.* (2014) chose the reference scenario for economic comparison to be the use of soil insecticides on continuous, non-Bt maize, the traditional approach to control for much of the 20th century. The model simulated the evolution of rootworm resistance to Bt maize, but did not simulate resistance to soil insecticides. They evaluated refuge sizes of 5–50% for single-trait Bt maize and 5–20% for pyramided Bt maize with two traits targeting the pest. Onstad *et al.* (2014) evaluated both block and blended (seed mixture) refuges. Results demonstrated that, for pyramided Bt maize, block refuges planted in the same location within a field year after year gave the greatest overall profit for a grower. If growers relocated their block refuge annually (which is the most common practice), then a 5% blended refuge gave the greatest return. For single-trait Bt maize, 10–20% blended refuges gave greater economic return compared with block refuges ranging from 5–50%. Single-trait Bt maize with 5–20% block refuge (with no insecticide) was superior to soil insecticide use alone in all maize fields (Onstad *et al.*, 2014). Thus, modelling the biological and economic system can help evaluate the options available for IPM and HPR.

We usually do not consider deploying HPR based on an annual decision using an economic threshold. However, if a life stage can be sampled in one season to make a decision about planting for the next, which is potentially the case for *D. virgifera virgifera*, then as Onstad *et al.* (Chapter 7) indicate, an economic threshold can be used. Crowder *et al.* (2006) used a simulation model of *D. virgifera virgifera* to determine whether sampling and economic thresholds in year *t* can improve IPM when Bt maize is used as the primary control tactic in year *t* + 1. When Bt maize killed at least 80% of susceptible larvae, the calculated economic threshold increased linearly as the proportion of susceptible beetles surviving the toxin increased (Crowder *et al.*, 2006). The use of economic thresholds slightly slowed the evolution of resistance to Bt maize. In areas with or without rotation-resistant pest phenotypes, the use of sampling and economic thresholds generated similar returns based on net present value compared with strategies of planting Bt maize every season. Crowder *et al.* (2006) concluded that farmers may be inclined to plant Bt maize every season, because sampling protocols can be costly and because Bt maize is extremely effective.

Over the past 20 years, numerous studies have demonstrated the profitability for farmers of most transgenic insecticidal crops sold in the US and around the world (Marra, 2001; Alston *et al.*, 2002; Naranjo *et al.*, 2008; NRC, 2010). Most of the analyses have focused on Bt cotton (Shelton *et al.*, 2002; Raney, 2006; Smale *et al.*, 2006; Naranjo *et al.*, 2008). For example, Brookes and Barfoot (2006) concluded that over a 10-year period, Bt cotton production increased farm income globally by $7.51 billion. This represented ~6.7% of the value of all cotton production worldwide. In 2005, nearly 80% ($1.38 billion) of the income benefits were garnered by farmers in developing nations (Brookes and Barfoot, 2006). Kathage and Qaim (2012) focused on the economics of Bt cotton production in India for the period 2002–2008. They determined that Bt cotton caused a 24% increase in cotton yield per acre through reduced pest damage and a 50% gain in cotton profit for small farms.

Conclusions

Kennedy (2008, p. 5) concluded that 'cultivars having moderate levels of resistance to important pest species have made enormous contributions to crop production in both major and minor crops worldwide, despite the fact that the underlying chemical and/or physical mechanisms conferring resistance are often poorly understood'. Peterson *et al.* (2017) urged breeders and entomologists to increase efforts to study and develop tolerance to insect damage to improve IPM. Tolerance is difficult to evaluate, but it has the major advantage of not putting selection pressure on the insects to evolve mechanisms counteracting antibiosis or antixenosis, the most common modes of HPR.

In Europe, some breeders and advocates of sustainable agriculture believe that current breeding programmes do not fulfil the needs of IPM (Lamichane *et al.*, 2018). Some believe that these programmes are market-driven and focused too much on conventional agriculture. Lamichane *et al.* (2018) state that the European regulatory systems inhibit the development of many more crop varieties that are needed to meet the agronomic and resistance needs of IPM-oriented farmers in unusual environmental conditions. Unfortunately, in a survey of 39 European experts, 87% stated that plant diseases, not insects, are given higher priority in native-trait breeding programmes for IPM (Lamichane *et al.*, 2018).

This emphasis on plant disease research is particularly true in the use of natural diversity to develop resistant fruit and vegetable varieties (Professor Jack Juvik, Illinois Plant Breeding Center, University of Illinois, 12 October 2018, personal communication). The genetics controlling crop resistance to plant pathogens is in many cases controlled by alleles segregating at a single locus to specific pathogens, which simplifies introgression of resistance. In contrast, resistance to insect pests can be much more complex where multiple genes can control phenotypic expression of resistance. In addition, selection for plant-pathogen resistance in a breeding programme is facilitated by laboratory or greenhouse pathogen inoculation often on seedlings or immature cuttings, which can expedite breeding progress and efficiency. Infestation of segregating breeding populations with insect pest species to assay for resistance has limitations in both greenhouse and field environments due to the need to generate sufficient insect populations to provide adequate and measurable expression of resistance (Dr Juvik, 18 October 2018, personal communication).

More research is needed to understand the economic influence of HPR on the value of livestock feed when native traits (alfalfa) or transgenic insecticidal traits (maize and soybean, *Glycine max*) are deployed (NRC, 2010). Feed costs make up nearly half the variable costs of livestock production, so changes in the price of feed can significantly affect the livestock market (NRC, 2010). Livestock producers may be the major beneficiaries of reductions in the prices of Bt maize. They also benefit from increased feed safety from the reduction of mycotoxins, which contaminate maize kernels damaged by insects (Wu, 2006).

Given that HPR is a fundamental component of agro-ecosystem designs for improved IPM, there is a need for more and better economic evaluations of HPR involving native traits. In particular, government agencies subsidizing research and development should document and publicize their efforts. This means not only the successes, but also the failures. Can HPR with any traits be taken too far with diminishing returns on investments in crops that have been studied for many years? Innovation is always risky, so some failures should be expected. Most HPR experts believe that the successes more than compensate for all the research. It should also be recognized that many research programmes are focused on crop improvement in general, not just HPR against insects. Thus, a new and different accounting may be necessary to separate the two parts of a programme.

Economic analyses of HPR could also benefit from a better understanding of farmer behaviour (Hurley and Mitchell, 2014). The need for refuges to make transgenic insecticidal crops durable and the hesitancy of farmers to plant unprotected refuges make it imperative that interdisciplinary research not only explain farmer behaviour but also suggest ways to change their behaviour, if necessary. Of course, much of this approach depends on whether we take the perspective of the farmer or that of other stakeholders when performing the economic analyses, and whether we adopt rational economics or behavioural economics as the paradigm. In any case, other social scientists may be able to contribute valuable expertise to these studies.

Note, too, that HPR is an IPM tactic that is more than just seeds. The tactic is a combination of the product, the timing of planting, the location of planting and other factors concerning the growth of the crop (Pilcher and Rice, 2003). All of these can be influenced by farmer behaviour.

Furthermore, all economic analyses should realize that the spatial scale and system boundaries are always subjectively chosen and should be carefully justified. Negative externalities of pest management that impact environments and organisms outside the identified system are often discussed. With regard to positive externalities, at least two studies have shown benefits outside of a cropping system with Bt crops (Wu *et al*., 2008; Dively *et al*., 2018). Dively *et al*. (2018) used historical data for crop production and pest management in the eastern United States to demonstrate regional reduction of *Ostrinia nubilalis* and *Helicoverpa zea* populations with widespread Bt field maize adoption (1996–2016) and decreased economically significant damage in vegetable crops (peppers (*Capsicum annuum*), green beans (*Phaseolus vulgaris*) and sweetcorn (*Zea mays*, convar. *saccharata*)) compared with the period before commercialization of Bt maize (1976–1995). In addition, the authors described significant decreases in the number of insecticides applied and O. *nubilalis* damage in vegetable crops during the same period of Bt maize adoption. Dively *et al*. (2018) concluded that their data demonstrate the need to account for offsite economic benefits of pest suppression, in addition to the direct economic benefits of HPR and Bt crops.

In summary, most of the published cases described in this chapter support the view that resistance by crops against insects is valuable over decades, not just single growing seasons. When the costs of HPR research and development have been estimated, the benefits exceed the costs over 10–20 years. These results should encourage others to continue the research and to take the extra steps to demonstrate the benefits to farmers and society.

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6

Economic Principles and Concepts in Area-Wide Genetic Pest Management

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Area-wide pest management has received significant attention from the biotechnology community as innovative methods permit more targeted manipulation of insect pest genetics to achieve control objectives. Approaches generally falling under the heading of genetic pest management (GPM; Gould, 2008) have advanced significantly within recent years, due to improvements in the underlying biological tools. Understanding the economic implications of GPM, in the broader context of integrated pest management (IPM), requires careful consideration of current and proposed GPM approaches.

Genetic modifications may take many forms with vastly different outcomes. A basic application could involve simple cost-saving enhancements of more traditional approaches such as the sterile insect technique (SIT) and biocontrol. New ‘self-propagating’ applications involve gene drives, which promise (or threaten) the potential eradication of a pest species from large geographic areas or, alternatively, the widespread replacement of a species population with less pestilent genotypes (NASEM, 2016; Noble *et al.*, 2018). Proposed hybrid schemes may also reduce – but not eliminate – populations while replacing surviving individuals with desired genetic alterations.

In this chapter, we will explore the key economic principles for the inclusion of genetically engineered insects within IPM programmes, discussing proposed examples with agriculture and health applications. Whereas other previous publications (reviewed below) have provided detailed technical guidance for economic analysis of GPM programmes, we seek here to highlight the application of general economic principles in GPM and its incorporation into IPM programmes, as well as to highlight productive areas for future applied bio-economic research.

The next section provides a brief overview of various GPM tools currently used or proposed. We then examine how the use of economic efficiency criteria can be used to determine the optimal configuration of a GPM programme, accounting for heterogeneous distribution of benefits and costs over time and space as well as principles for integration with other pest control activities. Subsequent sections examine how GPM tools, which tend to be centralized forms of pest control, can be expected to interact with individual (e.g. farmer) choices about their own pest control activities. We also discuss briefly some of the economic issues related to risks and potentially irreversible consequences of current GPM applications.

Overview of Technologies Created and Proposed

GPM approaches to area-wide pest control can broadly be characterized as *population suppression* or *population replacement* strategies (Alphey and Bonsall, 2018). The goal in population suppression is to reduce or eliminate pest populations from the production environment. This could include either

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simply suppressing populations below economic levels or extending to local or widespread eradication. In a replacement strategy, it is not the presence of the pest, rather the pathogen(s) it vectors that threaten human activity. A replacement strategy seeks to 'push' a new genotype through the wild population that reduces or eliminates its economic impact, e.g. by genetically blocking some aspect of the transmission pathway of the target pathogen within the pest.

Another key characterization of genetic systems is the extent to which germline changes can spread through the species population. Some systems are 'self-sustaining', in that selfish genetic elements are leveraged to bias inheritance and up to 100% of offspring of modified individuals inherit a target gene (e.g. Buchman *et al.*, 2018). This is also known as a 'gene drive', which is designed to potentially make permanent changes to the biotic environment by suppressing or replacing target populations. In theory, the release of a very small number of gene-drive modified insects could eventually spread changes throughout the species' populations. Other strategies are considered 'self-limiting', in that inheritance is not biased (i.e. only 50% of offspring inherit the gene) and continual releases would be necessary to maintain the modified genes in the environment. Self-limiting approaches are generally designed for population suppression programmes. However, field testing of self-limiting applications for resistance management, particularly for Bt insecticidal traits, has shown some promise to both *reduce* populations and heavily *replace* surviving individuals with renewed susceptibility (Zhou *et al.*, 2018). We will discuss specific applications of each of these approaches.

Proposed transgenic refinements to traditional SIT programmes

Area-wide management through direct alteration of insect pests is a long-established control method via the traditional SIT. The SIT uses radiation in mass rearing facilities in which immature males are separated from females, then irradiated and released to overwhelm wild male populations, reducing the likelihood of successful wild mating. The first target of a radiation-based SIT programme was the New World screwworm fly (*Cochiliomyia hominivorax*), a flesh-eating livestock pest that was eradicated from North and Central America from the 1950s to the 1990s (Scott *et al.*, 2017). Benefits accrued to the livestock sector due to absence of screwworm fly are estimated at over $1 billion annually (Vargas-Terán *et al.*, 2005). Continual releases of sterile males are required to prevent re-infestation and a release barrier is currently maintained in Panama, along with a rearing and production centre that employs about 400 people and is reported to cost $15 million annually (USDA-APHIS, 2017). Transgenic approaches aim to reduce very costly larval feed expenditures, which amount to $1.00 per 1000 insects (Mastrangelo and Welch, 2012). Through transgenic strains resulting in female-specific lethality in early instars, researchers have estimated SIT screwworm production costs could be reduced by about $1 million annually (Concha *et al.*, 2016). Even as benefits of the programme are substantial, continually minimizing rearing facility costs remains an important goal of the ongoing, long-term project (Scott *et al.*, 2017).

Conditional lethal approaches

Genetic conditional lethal systems, as a concept, may be incorporated as a cost-saving enhancement to traditional area-wide pest management systems or serve on their own as a primary control strategy (Alphey and Bonsall, 2018). One management strategy that has received significant attention due to applicability across a wide array of insect pest species is a dominant, repressible, female-specific lethality system known as RIDL, or 'Release of Insects with a Dominant Lethal' (Thomas *et al.*, 2000). Lines are engineered such that female larvae will die without the addition of an antidote (tetracycline) in the diet that 'switches off' expression of the lethal gene. This allows for mass rearing in factory settings but expresses female lethality in the field. Predominantly male-only releases of individuals homozygous for the lethal gene may then enable substantial population suppression, though the system is inherently self-limiting and cessation of releases would likely lead to natural removal of modified genes over time (Garziera *et al.*, 2017).

One argument made for RIDL versus radiation-based SIT emphasizes the reduction of release ratios, and hence production costs of release programmes, by decreasing the fitness costs that can result when high doses of radiation are required to adequately sterilize male insects. This approach is particularly valuable for certain lepidopteran species such as pink bollworm (*Pectinophora gossypiella*), which can severely impair competitiveness (Morrison *et al*., 2012). Described as a 'genetics-based variant of the SIT', RIDL approaches to genetic control that do not require the use of irradiation have been developed for many pests of agricultural significance including the diamondback moth (*Plutella xylostella*) (Harvey-Samuel *et al*., 2015), Mediterranean fruit fly (*Ceratitis capitata*) (Leftwich *et al*., 2014), pink bollworm (Morrison *et al*., 2012; Jin *et al*., 2013), and olive fly (*Bactrocera oleae*) (Ant *et al*., 2012).

Gene drives

Gene drives involve germline changes to insects that are preferentially inherited, facilitating the spread of traits throughout a species' population. Some natural 'selfish' elements exist in wild populations, such as the *Medea* element in *Tribolium castaneum* (Lorenzen *et al*., 2008), the *t*-complex in mice (Willison and Lyon, 2000) or the maternal inheritance of *Wolbachia* bacteria in many insect species (Moreira *et al*., 2009), causing non-beneficial traits to spread throughout global populations. The prospect for engineered drives has received renewed attention, including a dedicated report by the National Academies of Sciences, Engineering, and Medicine (NASEM, 2016), with the advent of CRISPR/Cas9 gene editing technology, which allows for more precise and less costly genetic manipulation (Jinek *et al*., 2012; Doudna and Charpentier, 2014).

Researchers have attempted to develop synthetic gene drives for multiple agricultural pests. The first known attempt at such a gene drive system for an agricultural pest was in Asian citrus psyllid (*Diaphorina citri*), an invasive citrus pest in the United States that vectors a devastating bacterial pathogen (*Candidatus liberibacter*) causing citrus greening disease (also known as Huanglongbing). The goal of the United States Department of Agriculture (USDA) funded 'nuPsyllid' project was to replace the wild population with a self-sustaining strain incapable of vectoring the bacterium. This *population replacement* strategy would not have removed Asian citrus psyllid from the environment, but would render it innocuous to citrus production.

In a *population suppression* application, a drive system has been created for the fruit fly, spotted wing drosophila (Buchman *et al*., 2018). *Drosophila suzukii* is an invasive species in the United States that causes extensive damage to soft berry and stone fruit crops and significantly increases management costs (Asplen *et al*., 2015). Spotted wing drosophila is uniquely equipped with a sharp ovipositor, which it uses to lay eggs inside ripening berries. There is a zero-tolerance policy for spotted wing drosophila presence in any fresh market or whole frozen fruit in the United States, possibly leading to rejection of entire shipments and heightening concern for control. A (species-specific) gene drive system would likely seek to supplant current reliance on broad spectrum insecticide spraying (Asplen *et al*., 2015).

While technically a form of biocontrol and not GPM, perhaps the largest-scale application yet of a selfish inherited element for pest control is the use of *Wolbachia* bacteria in disease-transmitting mosquitoes (Crain *et al*., 2013). Because of preferential inheritance, these intracellular bacteria are able to spread to fixation in insect populations, and specific strains introduced into *Aedes* mosquitoes have shown the surprising property of being able not only to suppress mosquito populations but also to block transmission of dengue, chikungunya and Zika viruses (Moreira *et al*., 2009; Dutra *et al*., 2016). While published cost-effectiveness analyses of *Wolbachia*-based mosquito control are not yet publicly available, large-scale deployments are now underway and being evaluated in Indonesia, Vietnam, Australia, Colombia and Brazil (Dorigatti *et al*., 2018).

Interaction with other pest control tools

As with any form of pest control (particularly in the context of other chapters in this volume), GPM tools should be considered in concert with IPM; that is, 'with all the tools on the table'. Later in this chapter, we discuss economic principles for integrating GPM with other control measures. Here, we first describe a particularly salient context where GPM has been developed or proposed for an explicit IPM objective: the mitigation of pesticide resistance. In the case of population suppression GPM, the attraction of using it for resistance management is that release of pests with genetically engineered traits and pesticide susceptibility provides the double benefit of reducing the overall pest population while simultaneously increasing the prevalence of pesticide susceptibility.

Existing proposals for using GPM to mitigate resistance have focused mainly on the case of insect resistance to Bt (*Bacillus thuringiensis*) crops. In tandem with planting non-Bt crop refuges and stacking multiple high-dose toxin traits, which is the current best practice in Bt crop stewardship

(Tabashnik *et al.*, 2013), researchers have promoted genetic control strategies to ease the burden of traditional measures and further slow (or reverse) resistance (Alphey *et al.*, 2007, 2009; Harvey-Samuel *et al.*, 2015; Zhou *et al.*, 2018). These proposals have been informed by previous experience with area-wide releases of irradiated (fully susceptible) SIT insects deployed to combat Bt resistance in the case of cotton production in the southwestern United States (Tabashnik *et al.*, 2010). In this programme, refuges were largely replaced with season-long release of sterile pink bollworms and other control tactics as part of eradication efforts. Economic losses for Arizona cotton growers from yield reductions and insecticide sprays before Bt cotton was introduced were about $18 million/year. After Bt cotton planting this dropped to $5.2 million/year from 1996 to 2005, and then dropped precipitously to only $170,000/year during the SIT eradication programme from 2006 to 2009 (Ellsworth *et al.*, 2010). The researchers note that 'this program has benefited from a strong grower commitment, public investment in sterile insect technology, a well-developed infrastructure for monitoring pink bollworm resistance and population density, virtually 100% efficacy of Bt cotton against pink bollworm, and this pest's nearly exclusive dependence on cotton in Arizona' (Tabashnik *et al.*, 2010, p. 1306). Additional indirect benefits of retaining Bt susceptibility and reduced insecticide use included natural enemy and non-target pest conservation, human health benefits from decreased exposure and environmental benefits (Naranjo and Ellsworth, 2009).

Similar outcomes have been modelled (Alphey *et al.*, 2007) and tested in confined cage trials (Harvey-Samuel *et al.*, 2015; Zhou *et al.*, 2018) with a transgenic variant of the SIT programme using mass releases of fully susceptible insects with a RIDL construct. Such releases not only maintain a genetically susceptible population but also suppress or locally eradicate the target pest.

Economic Principles for Efficient GPM

As compared with more widely adopted control measures such as conventional pesticide applications and the use of Bt crops, GPM tools differ substantially in the structure of their benefits and costs. Like predecessors such as radiation-based SIT (Mumford, 2005), these differences arise according to how these benefits and costs are distributed over time and space. Because all GPM approaches so far involve mass-rearing and release of genetically engineered insects, costs tend to be centralized and incurred in the short term, whereas benefits are area-wide and accrue over the longer term. This structure of benefits and costs generates unique challenges and opportunities for evaluation and implementation in an IPM context. We review the structure of these costs and benefits below, before combining this information in a simple mathematical decision analysis model for efficient GPM.

Fixed and recurring costs of GPM

Even setting aside the research and development costs (a topic we do not address in this chapter), mass rearing and release (MRR) of genetically engineered pests are expensive undertakings. We divide these costs into fixed and recurring. Fixed costs refer here to the costs of establishing a facility, related to design, construction, regulatory permits, etc. Recurring costs (also referred to as operational costs) are all those expenses incurred in generating a continual flow of genetically engineered insects for release, as well as the costs of those releases (e.g. aerial deployments). This demarcation is important from a decision analytic perspective, because after the fixed costs of facility establishment are incurred, they are sunk and hence should have no direct impact on decisions about that specific release programme going forward (though fixed costs can certainly affect decisions to initiate future release programmes).

To date, the most systematic, publicly available quantitative information on fixed and operational costs of MRR is provided by Alphey *et al.* (2011). In developing a model to assess the cost-effectiveness of a RIDL system for *Aedes aegypti* to control dengue, they compile comparable cost information for a range of MRR projects around the globe going back to the 1970s. Quinlan *et al.* (2008) also provide extensive discussion and qualitative comparisons of the building costs of MRR facilities. To these data, we also add cost information for the New World screwworm MRR facilities built in Florida and Texas in 1958 and 1962, respectively (Spradbery, 1994).

Figure 6.1 shows the relationship between sunk costs and capacity across the different facilities. Despite being constructed in a variety of countries for very different pests and contexts, there appears to be surprisingly consistent evidence for significant

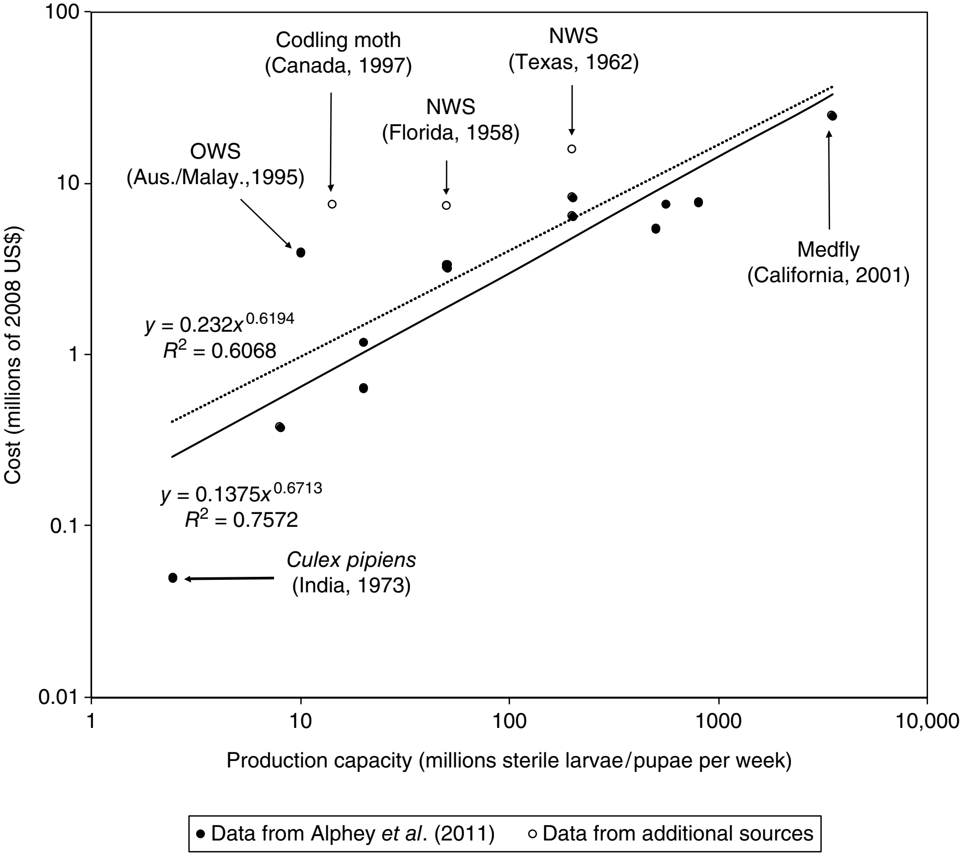

Fig. 6.1. Sterile insect rearing facility costs by capacity. NWS, New World screwworm; OWS, Old World screwworm. Plotted lines obtained from an ordinary-least squares regression (OLS) of log(cost) on log(capacity), with best-fit equations converted back to power law functions and R^2 shown in figure. Dotted line is fitted to the subset of observations corresponding to Mediterranean fruit fly SIT. (Codling moth data from Bloem and Bloem, 2000, NWS data from Spradberry, 1994, remaining data from Alphey *et al*., 2011.)

economies of scale. That is, fixed costs increase less than proportionally with total facility capacity. This can be seen in the figure from the plotted regression lines having slopes less than one; see Appendix 6.1 for a discussion of the assumptions, limitations and additional statistical tests in this regression analysis. Because these linear regression lines are plotted on a log scale for both variables, they imply that facility costs $C(k)$ as a function of capacity k are $C(k) = \alpha k^{\beta}$, where $\alpha > 0$ and $\beta > 0$ are constants. When $\beta < 1$, this function $C(\times)$ is concave and exhibits economies of scale.

Analysis of the data in Fig. 6.1 produces estimates of β between 0.619 and 0.671, depending on whether the New World screwworm and codling moth data are included. These estimates are nearly identical to an estimate of $\beta = 0.622$ yielded from previous analysis specifically of Mediterranean fruit fly MRR operations (Quinlan *et al*., 2008, p. 170; Fig. 6.1). This β parameter is an estimate of the *elasticity* between facility costs and capacity, meaning that a 1% increase in facility capacity is associated with between a 0.619% and 0.671% increase in fixed costs. The fact that these parameter estimates remain so stable with inclusion of different species (with significantly different MRR operations and resulting costs, Quinlan *et al*., 2008, pp. 141–148) suggests the evidence for economies of scale is robust.

Appendix 6.1 presents strong statistical evidence for economies of scale in Mediterranean fruit fly facilities, but shows the evidence is much more ambiguous for other species. This appendix also discusses the conditions under which this parameter estimate β from a pooled regression can be viewed as an unbiased average across species and contexts that may have varying degrees of scale economies. We also test in the appendix the assumption that the cost function takes the power law (a.k.a. log-linear) form, $C(k) = \alpha k^{\beta}$, and find strong statistical evidence for this specification.

Economies of scale generally are understood to arise because of fixed factors of production that do not vary with the amount of output. In the case of MRR, such factors could include administrative and facility-level research and development costs (Quinlan *et al.*, 2008). However, alternative facility formats, in particular the use of independent production modules instead of a single centralized facility, may forego these economies of scale for other advantages, such as reduced losses from pathogen contamination and flexibility in spatial and temporal distribution of releases (Quinlan *et al.*, 2008, p. 148). To the extent they are present, economies of scale have implications for decisions about the economically efficient scale of production capacity in MRR, which we show below in the context of a simple decision analysis model.

There appears to be a much less obvious pattern between recurring operational costs of facilities and production levels. Analysing their compiled data, Alphey *et al.* (2011, p. 7) conclude 'there is no such discernible pattern to data on budgeted or actual operational costs for SIT facilities'. This contrast with the clearer pattern to fixed costs in Fig. 6.1 could arise because of operational costs being more inconsistently reported across applications (e.g. are both rearing *and* release included?), or because the nature of operational costs is more heterogeneous than fixed costs (e.g. by species, with more expensive meat-based diets in screwworm rearing, or by differing geographies for release environments). Statistical analysis of heterogeneity in operational costs (including monitoring costs) of MRR would be a useful area for future applied research.

Distinctions of GPM benefits over time and space

Perhaps even more than with costs, the benefits of GPM tools are likely to vary significantly with the nature of the specific technology used. This can be most starkly appreciated by comparing a 'conventional' GPM tool such as RIDL with newer, self-propagating gene drive tools. As a GPM form of traditional SIT, RIDL requires continual releases over time to maintain pest reductions, and the ultimate spatial extent of these reductions is dictated by the extent of the release area. In contrast, a highly efficient self-sustaining gene drive could involve a single initial release, which could then spread unimpeded through the entire population. If the drive is designed for population suppression, it thus has the potential to permanently eliminate the pest locally, or even to globally eradicate it (Burt, 2003). This feature of gene drives is a key reason for their appeal to proponents (and a key factor in the perceived risks they pose). While the cost per insect for a gene drive release is likely to be comparable with more conventional GPM, far fewer gene drive insects would need to be released to accomplish a given level of reductions over time, if the technology worked as intended. Due to increased risk accompanying increased ability to penetrate a species population, it is possible that cost reductions in rearing and release of gene drive insects may be dampened by greater regulatory or surveillance costs. This remains to be seen as programmes mature.

Another significant distinction between the costs and benefits of GPM tools in general is that the area-wide nature of GPM benefits leads to their *non-excludability*. This means, for example, in the case of agricultural pests, that farmers in the release area will benefit from these tools regardless of whether they pay for them. This is an important economic property we will elaborate on further below.

Finally, because of the relative novelty of GPM, especially gene drives, their benefits and risks tend to be characterized with deeper uncertainty than the direct costs of producing and releasing genetically engineered pests. Because many of these technologies have not yet been evaluated in field releases (which is likely to change in the near future, particularly in the case of the *Wolbachia*-infected mosquito releases described above), estimates of their benefits tend to rely heavily on bio-mathematical modelling, with results generally showing how the benefits can vary significantly with currently unknown biological parameters in these models. For example, modelling has informed most of our understanding about how well gene drives can be expected to function (Noble *et al.*, 2017), how they might spread (intentionally or otherwise) across populations (Dhole *et al.*, 2018) and the extent of their potential reversibility (Vella *et al.*, 2017).

A simple intertemporal decision model for efficient GPM

Here we set up a basic model of a decision maker seeking to identify an economically efficient plan for implementing a GPM programme over time. After we set up this model, we use it to discuss a number of economic forces to consider in GPM.

Consider a situation in which a centralized decision maker (e.g. a department of agriculture or growers' association) is considering implementation of an agricultural GPM project. The decisions to be made are initially how large a rearing facility to construct and then, once constructed, the intensity and timing of releases. An array of growers, indexed by $i = 1, \dots, N$, in the area will benefit from the project. Following previous discussion, the facility construction cost is given by $C(k) = \alpha k^{\beta}$, with $\alpha, \beta > 0$ and $\beta < 1$, i.e. increasing returns to scale in capacity, k, the number of genetically engineered insects. After construction, and assuming a planning horizon of T periods, the decision maker must determine in each period $t = 1, 2, \dots, T$ how many genetically engineered pests to release, $r_t \leq k$. For simplicity, we omit a salvage value of the rearing facility at the end of the time horizon (and, in any case, we might allow the time horizon to be infinite or indeterminate). The benefits of the release are reduced pest damages. Suppose that pest damages to grower i are given by the function $d_i(P_t)$, where P_t is the area-wide state of the pest population at time t. The operational recurring costs of releases, meanwhile, are given by $c(r_t)$. Finally, suppose we have some biological model for the pest population dynamics, and how these respond to GPM releases; suppose we can characterize this model as some function $F(P,r)$, such that $P_{t+1} = F(P_t,r_t)$. In terms of this mathematical notation, the decision maker's optimization problem can therefore be described as one of first choosing the efficient capacity k, and then choosing the efficient release schedule $r_1, r_2, \dots$ and so on, subject to the capacity constraint $r_t \leq k$. These decisions produce a distribution of benefits and costs over space and time, with fixed costs of $C(k)$ incurred in the initial period and a flow of pest damages $d_i(P_t)$ to each grower i, to be reduced by releases via effects on the pest population dynamics in the function $F(P,r)$, and the centralized recurring costs $c(r_t,k)$ of those releases, given facility capacity of k. While this model could be further elaborated to allow for a grower-specific pest population state $P_{i,t}$, this complication is unnecessary for any of the points we want to make in this chapter.

To determine the efficient configuration for the programme, we have to first define our objective, in particular how to aggregate benefits and costs over growers and over time. The conventional approach (e.g. in benefit–cost analysis; Mumford, 2005) is to use the net present value (NPV) criterion, which weights each grower's pest damages equally in computing total damages, and to sum net benefits over time using a per-period discount rate of $\delta \geq 0$. With discounting, \$1 of benefits in period t is worth $(1 + \delta)^{-t}$ in today's dollars; the higher δ or t are, the less future benefits and costs are worth in today's dollars. The discount rate is often interpreted as reflecting the opportunity cost of alternative investments, assuming an appropriate market rate of return. The US Government Office of Management and Budget (OMB), for example, has historically advised government agencies to produce benefit–cost analyses using annual real discount rates of 3% and 7% (OMB, 2003), meaning \$100 in benefits next year (removing any anticipated price inflation) is worth only \$97.08 (at 3%) or \$93.46 (at 7%) in today's dollars.

With discounting equal weighting of growers' reduced damages, the NPV of costs plus damages in the GPM programme is:

$$\mathrm{NPV} = \underbrace{\sum_{t=1}^{T} \frac{\sum_{i=1}^{N} d_i(P_t) + c(r_t,k)}{(1+\delta)^t}}_{\text{recurring damages and costs: } \Gamma(\mathbf{r})} + \underbrace{C(k)}_{\substack{\text{fixed}\\ \text{costs}}} \qquad \text{(Eqn 6.1)}$$

An economically efficient plan is one that minimizes the NPV of pest damages plus programme costs. However, it is important to note that this is only one among a number of possible objectives the decision maker could seek to optimize. For example, instead of weighting each grower's benefits equally, we could consider a criterion that contains equity motivations on the part of the policy maker. For example, we might weigh more heavily the impacts of the project on small-scale producers or farms whose survival is threatened by the target pest. Likewise, rather than using the NPV criterion with a positive discount rate to aggregate benefits and costs, the decision maker could weight net benefits in all periods equally (i.e. set $\delta = 0$) or to maximize net benefits according to a sustainability constraint (Heal, 2000). Nonetheless, we follow the approach of a standard benefit–cost analysis here, weighting across growers and a positive discount rate.

Choosing a capacity and release schedule to minimize the NPV of costs and damages can be broken down into a two-stage decision problem:

- *Step 1*: For a given capacity constraint of k, choose a release schedule $\boldsymbol{r} = \{r_1, r_2, \ldots, r_T\}$ that minimizes the recurring costs and damages, $\Gamma(\boldsymbol{r})$, component of NPV above, subject to the given capacity constraint $r \leq k$ and the biological dynamics $P_{t+1} = F(P_t, r_t)$. This yields an optimized release schedule $\boldsymbol{r}^*(k)$, conditional on the capacity constraint. Substituting this back into the recurring damages/cost $\Gamma(\boldsymbol{r})$ function gives us $\Gamma^*(k) := \Gamma[\boldsymbol{r}^*(k)]$, i.e. optimized recurring net benefits may be viewed as a function of the given capacity constraint.
- *Step 2*: Choose a capacity level that minimizes $NPV(k) = \Gamma^*(k) + C(k)$.

This is a backwards recursive process for solving this decision analysis problem. In Step 1, we first must consider what an optimized GPM release looks like across a range of different capacities, only accounting in this step for the benefits from pest damage reduction and operational costs. Once we have this information, Step 2 weighs the NPV of these benefits and operational costs against the costs of establishing facilities with different capacities.

Step 2 of this model simplifies to minimizing programme costs and pest damages over a single variable: facility capacity k. Intuitively, the recurring optimized cost/damage function $\Gamma^*(k)$ is generally *decreasing* in k: if a GPM facility materialized out of thin air, the greater its capacity the more pest control we could accomplish. (In effect, this function's negative, $-\Gamma^*(k)$, captures the benefits of a GPM facility/programme of capacity k, meaning that these benefits are increasing with capacity.)

Several distinctive features of GPM and related SIT programmes are likely to cause deviations from the standard economic analysis, which imposes assumptions on the shape of the *marginal costs* and *marginal benefits* curves. These standard assumptions, if true, imply that economic efficiency is obtained at the point in which marginal benefits equal marginal costs. We explain why these assumptions must be relaxed in our context and why a more detailed analysis is required to identify the economically efficient facility capacity. We then show, in the context of GPM, that the equalization of marginal benefits and costs is likely a necessary, but not sufficient, condition for efficiency.

First, a conventional economic model would probably assume that facility fixed costs are increasing at an increasing rate $C(k)$, i.e. *increasing marginal costs*: that each additional unit of capacity is a little bit more costly than the last. However, as Fig. 6.1 shows, fixed costs of establishing GPM facilities appear to exhibit economies of scale (i.e. *decreasing* marginal costs), at least over the empirical scales observed to date.

Second, in standard economic analysis, we would also expect $\Gamma^*(k)$ to not only decrease, but to do so at a decreasing rate. That is, in a conventional economic model, we assume *diminishing marginal benefits* of the programme: every additional unit of capacity gives us a little bit less than the last. However, the nature of all GPM technologies described implies that the pest reduction benefits almost certainly do not adhere to this assumption. Without delving into mathematical details of modelling pest population dynamics and genetics, biological models of the technologies described above generally suggest two sensible characteristics of $\Gamma^*(k)$:

1. The potential reduction in pest damages is finite (limited, for example, by the total damages that would be avoided if the pest were completely eliminated from the target area). This means $\Gamma^*(k)$ has a finite lower bound, no matter how big the capacity k.
2. Because of the minimum release thresholds (ratio of densities of modified and wild-type insects) that are typically required to achieve any positive benefit from any GPM programme, facilities that are too small in capacity to overcome this threshold will effectively yield zero pest reduction benefits (Mumford and Carrasco, 2014). In terms of the shape of $\Gamma^*(k)$, this means the marginal damage reductions, i.e. the benefits of GPM, are likely to be nearly zero below this threshold.

In what follows, we also impose the normalization $\Gamma^*(0) = 0$. This means we are expressing recurring pest damages/costs at all capacities, relative to a baseline where no GPM ($k = 0$) is deployed. (This also means the benefits function, $-\Gamma^*(k)$, which is increasing in k is always non-negative.)

These two characteristics and the normalization imply an approximately S-shaped benefits function. That is, initial marginal benefits at small capacities are essentially null. But as capacity increases, marginal benefits of GPM are likely to increase for biological reasons, e.g. each additional genetically engineered pest that can be released per period by slackening the capacity constraint can further contribute to reduced future population growth (Alphey and Bonsall, 2014). However, because there must logically be some upper bound to the benefits of increasing capacity (i.e. a limit to the pest damage reductions that are possible), marginal benefits must eventually decrease, leading to an S-shaped benefits function and an inverted U-shaped (or V-shaped) marginal benefits function. Based on the power–function facility cost curve supported by the statistical analysis above, the cost and benefits will always intersect at the origin and possibly at one other point with a positive capacity $\bar{k}$; at these points net benefits are zero. If such a $\bar{k} > 0$ exists, the mathematics of this model imply the (possibly non-unique) efficient capacity level k^* is somewhere between zero and $\bar{k}$. When no such case exists where $\bar{k} > 0$, this implies costs are always greater than benefits for any $k > 0$, so that the efficient decision in this case is simply not to undertake the GPM programme.

Figure 6.2 shows facility fixed costs, $C(k)$, and benefits net of variable costs, $-\Gamma^*(k)$, for three different GPM technologies. Panel (a) of the figure shows total costs and benefits, and panel (b) shows their marginal counterparts. The three GPM technologies, shown as the dotted lines from right to left in each panel of Fig. 6.2, are: (i) a conventional SIT-type GPM technology for which the optimal capacity is k_0, (ii) another conventional GPM technology that is more efficient but still requires continual releases (e.g. RIDL) for which the optimal capacity is k_1, (iii) and lastly a self-propagating GPM technology such as a highly effective gene drive for which the optimal capacity is k_2 and requires only limited releases to achieve its maximal benefit. Note the optimal capacities all occur where the downward-sloping portion of the marginal benefits curve intersects the marginal costs curve. Panel (b) makes clear that our standard economic efficiency criterion, equalization of marginal benefits and costs at the efficient capacity level (i.e. $-\frac{d\Gamma^*}{dk} = \frac{dC}{dk}$) is a necessary but sufficient condition for efficiency condition in the case of GPM capacity decisions: Each marginal benefits curve in panel (b) intersects the marginal cost curve at two points. The rightmost points of intersection reveal the efficient capacity levels. (The leftmost points of intersection in fact *maximize* total costs and damages across the range of capacities shown in the figure – clearly an outcome to be avoided.)

Compared with the least efficient conventional GPM, the more efficient conventional GPM method can be expected to require a smaller facility capacity to achieve the same level of total and marginal benefits. However, the more efficient conventional GPM method is simply shown as a shift left in the benefits curve, with no change in the curve shape. In particular, both of the marginal benefits curves for these conventional GPM technologies (Fig. 6.2, panel b) increase and decrease relatively little over the range of relevant capacities. In economic terminology, this means marginal benefits are relatively *elastic*: a shift upward in the marginal cost curve, for example, would translate into a relatively large percentage decrease in the optimal capacity. As shown in panel (a) of Fig. 6.2, this is because benefits increase and decrease relatively smoothly with capacity, and the logical response to a cost increase would be to give up some benefit from higher capacity to keep the operation efficient. Compare this to the self-propagating GPM technology, conceptualized here as a gene drive. Most models of these technologies imply that there exists a release threshold, above which the technology may achieve self-sustaining spread within the target area, requiring no further releases (barring reinvasion). Additional releases may still be beneficial, by accelerating spread of the technology through the population (resulting in earlier, less time-discounted accrual of benefits), but the self-sustaining aspect of the technology would be expected to lead to a fundamental change in the structure of these benefits. Here, that structure is conceptualized as an extreme increase and decrease in marginal benefits around the functional release threshold, k^*. Because of the steepness of the marginal benefits curve, i.e. the fact it is *inelastic*, the optimal capacity k_2 for this technology is just above this release threshold. Moreover, if we again imagine an increase in costs – a shift upward in the marginal cost curve of panel (b) in Fig. 6.2 – we see, in contrast to the conventional GPM technologies, the optimal capacity would change relatively little. This captures the intuition that with a technology like a gene drive, the key information needed by the decision maker is the release threshold k^*, because for efficiency we would wish to construct a facility that had the capacity to produce a single release just a little bigger than this threshold.

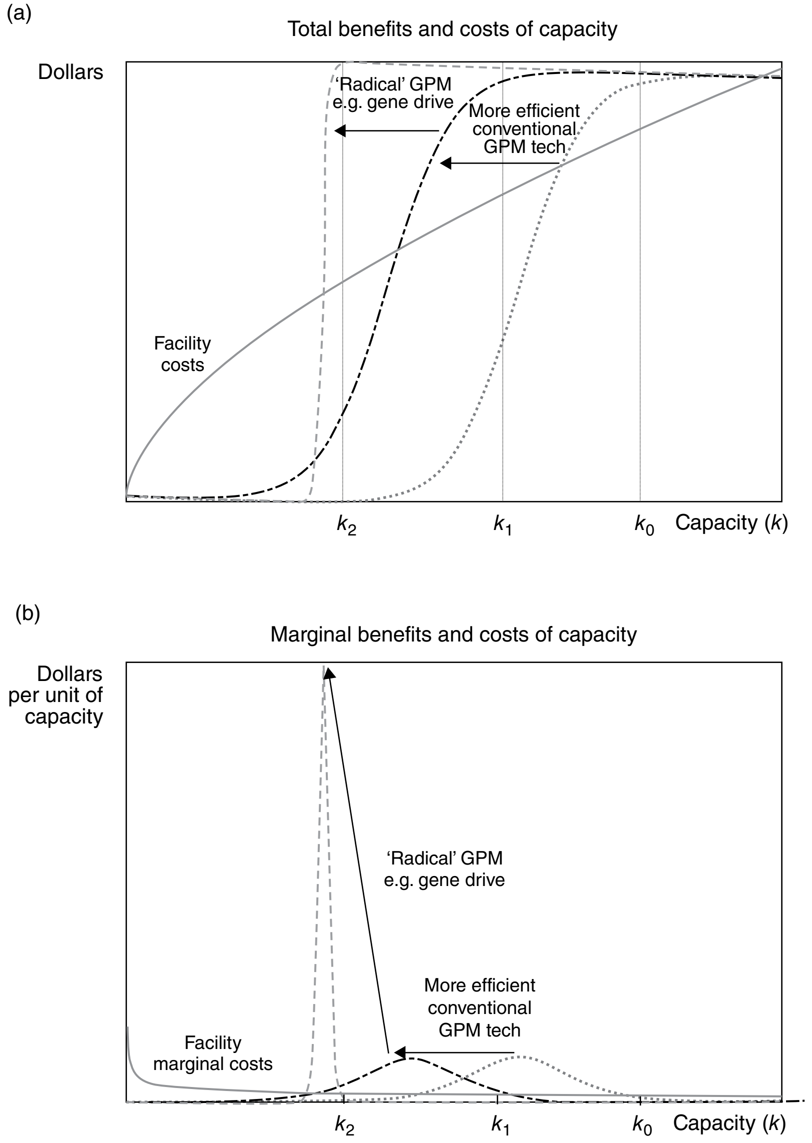

Fig. 6.2. Conceptual diagram of benefits and costs of GPM rearing facility capacity. Solid lines are total and marginal costs functions from Fig. 6.1. Dotted lines are benefits functions, from right to left in each panel for (i) conventional GPM, (ii) more efficient conventional GPM and (iii) self-propagating GPM, e.g. gene drive.

Spatial considerations in GPM planning

The spatial pattern of MRR programmes is also an important determinant of programme effectiveness, and the interactions between the timing and locations of releases across an area or region determine how quickly and over what area pest damage reductions can be expected to manifest. Mumford and Carrasco (2014) and Mumford (2005) discuss the two well-known examples of New World screwworm and Mediterranean fruit fly SIT control programmes in North and Central America, in which sterile insect releases moving from north to south were viewed as most practical for ecological and geographic reasons. In the case of the New World screwworm, these staged releases proceeded to eliminate the pest from the US, Mexico and continuing to the border between Panama and Columbia, where maintenance releases continue to prevent reinvasion from South America (Scott *et al*., 2017).

Another important spatial consideration is the careful definition of the boundaries of the overall management programme (Mumford, 2018). Even though modified pests released into the environment spread without recognition of administrative, political or economic boundaries, consideration of these boundaries in planning is important for efficient resource allocation and stakeholder support. Because GPM is often discussed with the explicit aim of locally eliminating a pest from a target area, Mumford and Carrasco (2014) note the importance of factoring in the costs of control buffers to prevent reinvasion once the pest has been eliminated from the management area. Mumford (2018, p.342), for example, demonstrates the role this buffer plays in determining programme boundaries and overall costs, in an application of the CLEANFRUIT spatial planning tool for a Croatian Mediterranean fruit fly SIT control programme.

Other organism-specific spatial considerations can also affect GPM programme costs and performance. In general, the closer the release point to the rearing facility, the cheaper the transport costs, with aerial releases being required for programme feasibility in most cases (Mumford, 2018). This creates a trade-off in facility siting and construction, between capturing the economies of scale documented above for fewer, larger facilities and the reduction in transport costs from many smaller facilities.

These spatial planning principles generally also apply to self-propagating forms of GPM, such as gene drives. Because gene drives are designed to achieve self-sustaining spread, there are both economic and ethical concerns about whether this form of GPM can be limited to a target area (NASEM, 2016). Spatially self-limiting drives are being developed to address these concerns, with the intention of being able to achieve permanent alteration (including elimination) of a local population, while being able to control *where* the drive spreads. The model-based analysis by Dhole *et al.* (2018) evaluated the degrees of self-sustaining spread, permanence and spatial delimitation of different forms of these technologies. They find the degree of a drive's spread to non-target populations depends strongly on migration of pests between target and non-target areas, and that there appears to be a trade-off between the degree of spatial control and the release thresholds required to obtain permanent conversions of the local populations. While increasing this release threshold may increase the optimal rearing facility capacity (right shift of k_2 in Fig. 6.2) and associated costs, the value of reducing the risk of spread to undesired areas may be economically (and ethically) warranted.

The extensive modelling of different GPM technologies (referenced above) is also amenable to landscape-level mathematical bio-economic analysis. Such analysis has been widely applied over the past decade to investigate economically optimal management strategies for invasive species over space (Epanchin-Niell *et al*., 2012; Epanchin-Niell and Wilen, 2012; Aadland *et al*., 2015; Kroetz and Sanchirico, 2015). While heuristics have been developed for deciding the patterns and timing of GPM and SIT releases over the landscape (Kean *et al*., 2007), computational bio-economic optimization techniques can yield non-intuitive prescriptions for more efficient management plans. For example, in an invasive species context, Epanchin-Niell and Wilen (2012) find realistic settings in which it is optimal to completely abandon control of a bio-invasion right as it reaches an inflection point in its growth and spread, before reapplying targeted control in later time periods to protect high-value sites. The economic gain from this sort of strategy would be unlikely to have been recognized without the aid of computational modelling.

Monitoring and local eradication

GPM and related SIT programmes are not only area-wide by design, but also typically implemented with the explicit goal of completely eradicating the pest, invasive species or disease vector from the target area (Barclay, 2005). Verifying eradication requires monitoring, which is costly. While monitoring is also a foundational concept in IPM, its purpose in GPM is somewhat different. A core IPM principle is to monitor prior to active control (often chemical-based), to prevent overuse of controls and delay emergence of pest resistance (Radcliffe *et al*., 2009). In contrast, GPM and SIT programmes are typically envisioned as continuing active control *until* monitoring establishes with sufficient confidence that the pest has been eradicated from the target area (or replaced with a non-harmful strain) so that releases can be discontinued (Vreysen, 2005). Beyond reduced damage for growers, officially declaring an area 'pest-free' may have significant economic benefits in removing barriers to international trade, e.g. in Mediterranean fruit fly eradication.

Because the probability of detecting relatively rare remnant populations is directly related to the intensity and extent of sampling, Vreysen (2005, p. 350) argues sampling should be implemented 'so as to maximize the probability of detecting relic insects in the field'. However, this objective omits the costs of sampling, and therefore evidently recommends unlimited sampling. As Liebhold *et al.* (2016) note, the recognition of positive sampling costs leads to a tradeoff between these costs vis-à-vis those of eradication (Fig. 6.3), e.g. via a rear-and-release GPM or SIT programme. This is because the less sampling is conducted in monitoring, the longer and more intensive the eradication programme must be to sufficiently ensure eradication. Vreysen (2005, p. 350) makes a similar point when noting the difficulty in deciding how long to continue a SIT programme after sampling fails to detect pest presence. Logically, the sparser the surveillance effort, the longer the releases must continue to achieve the same level of confidence in eradication. As Fig. 6.3 shows, this logic implies there exists some optimal density of surveillance points that minimizes the costs of an eradication programme. This diagram can be used to conclude, for example, that an exogenous reduction in eradication costs, which would be represented by a downward-leftward shift in the eradication cost curve, implies a reduction in the optimal amount of surveillance, whereas an exogenous reduction in surveillance costs implies an increase in the optimal amount of surveillance (and concurrently longer GPM releases).

Designing effective monitoring for GPM is also closely tied to the spatial considerations in programme design mentioned previously. Prescriptions for monitoring in previous SIT programmes have emphasized the importance of non-uniform monitoring across time and space, e.g. increasing sampling

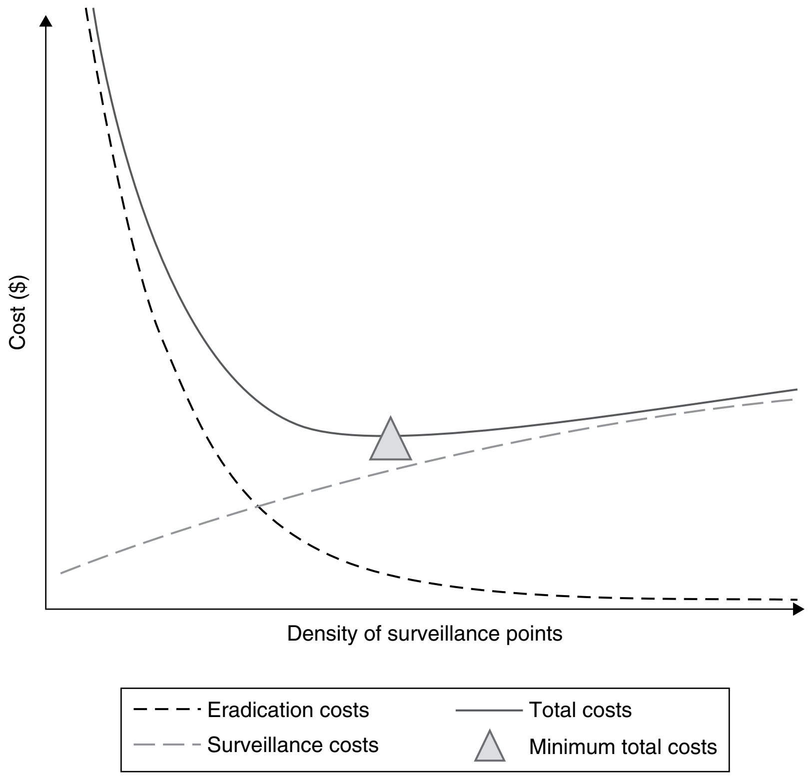

Fig. 6.3. The costs of monitoring and eradication. (From Liebhold *et al.*, 2016.)

around 'hot spots' (Vreysen, 2005, p.349). Another important spatial consideration in monitoring is specific to gene drives (and other invasive forms of GPM): the containment of the gene drive within the target area. Lessons from the ecological literature on invasive species may again be informative for gene drive containment monitoring. For example, Epanchin-Niell *et al.* (2012) show that spatial heterogeneity in establishment probabilities and monitoring costs can strongly affect the spatial configuration of efficient monitoring efforts.

Integration with other control measures

As noted above, just as with any control measure, GPM tools should be considered jointly within an area-wide IPM framework. That the IPM framework is *area-wide* is important because GPM tools generally only make sense at an area-wide scale (as discussed above), whereas IPM can tend to default to 'field-by-field' management (Vreysen *et al.*, 2007). Because the decision analysis model presented above implies the use of some advanced mathematics or computer modelling to determine the optimal release schedule $r_1, r_2, \ldots$, there are few general principles that have been derived for integrating the release schedule itself into an IPM framework. Derivation of such principles, e.g. by incorporating GPM into prior bio-economic optimization models of invasive species, agricultural pest and disease vector control (Qiao *et al.*, 2008; Marten and Moore, 2011; Brown *et al.*, 2013; Liebhold *et al.*, 2016) would be a useful area of future research. However, we discuss two useful general principles – one based on pest population dynamics and the other based on economic efficiency.

As with traditional SIT (Mangan, 2005), integration of GPM within a larger IPM programme is not only economically attractive, but usually essential to reduce pest densities to levels low enough to make GPM feasible. Like SIT, all currently proposed GPM technologies, barring the most highly invasive gene drive variants, require releases to exceed a threshold ratio between modified and wild-type insects. This 'reduce and release' principle is primarily a product of pest population dynamics. For pests with naturally high densities, even small threshold ratios can quickly require construction of prohibitively large and expensive MRR facilities if GPM were pursued in isolation without the aid of complementary pest suppression measures. And even with self-propagating GPM technologies such as gene drives, these release ratios are likely to still be significant (Vella *et al.*, 2017; Dhole *et al.*, 2018), requiring complementary IPM tactics. However, by first reducing densities, population suppression GPM systems can become highly effective, by attenuating growth rates before the population is able to take off from previously suppressed levels. Complementary pest suppression measures used for this purpose in SIT have included all of the standard tools of IPM (Mangan, 2005).

Another important principle for efficient integration of GPM with other controls is to choose a suite of control measures at scales such that their incremental returns on their individual investments are equalized. This principle is analogous to 'no arbitrage' principles in financial portfolios and investment theory (for an example application to IPM, see Schumacher *et al.*, 2006). To see how it applies here, consider the decision about GPM facility capacity described above, in combination with some other costly area-wide (or region-wide) pest control decision. For example, in the case of resistance to Bt crops, consider the decision of what the optimal refuge size R should be (assuming here this is fixed over time), and how this is affected by a MRR-based GPM programme (Zhou *et al.*, 2018). Suppose the costs of this refuge (e.g. in terms of enforcement, other administrative costs or foregone farm profits) is $Q(R)$. We model the benefits – in terms of the NPV of pest damage reductions – jointly as a function $B(k,R)$ of the optimal GPM facility capacity and refuge size R. For example, a larger-scale GPM programme might be associated with lower marginal benefits of refuge, i.e. $\frac{\partial B}{\partial R}$ is decreasing with k (though we do not assume this to be the case). The unconstrained version of the equi-marginal principle implies the marginal net benefits from each investment are both zero (as in Fig. 6.2b) and hence equalized, i.e. $\frac{\partial B}{\partial k} - \frac{dC}{dk} = \frac{\partial B}{\partial R} - \frac{dQ}{dR} = 0$.

However, we can better understand the tradeoffs between these alternative (or complementary) tools if we think instead about a decision wherein we seek to achieve a predetermined level of pest reduction benefits $\bar{B}$ (in NPV terms, i.e. discounted and summed over the time horizon) at least cost. This is a question of cost-effectiveness. That is, we seek to minimize total expenditure $C(k) + Q(R)$ such that $B(k, R) = \bar{B}$. Alternatively, we could seek to maximize pest reduction benefits, subject to a fixed budget constraint. For either objective, the *second equi-marginal principle* dictates that the cost-minimizing or benefit-maximizing combination must be such that a marginal dollar of expenditure on GPM produces the same marginal pest reduction benefits as a dollar of expenditure on refuge (or any other form of pest control). These equi-marginal principles apply in a wide variety of agricultural, environmental and public health contexts.

One advantage of this kind of cost-effectiveness analysis, unlike the NPV criterion, is that the benefits do not need to be monetized, only the costs. This is useful for public health or environmental applications of GPM, where monetizing benefits – e.g. of preventing deaths or saving endangered species – is generally more difficult (or controversial). For example, for GPM applications to mosquito vectors of dengue (Alphey *et al.*, 2011) or malaria, best practices issued by the WHO (Edejer *et al.*, 2003; Marseille *et al.*, 2014) recommend measuring programme effectiveness in terms of the discounted sum of disability-adjusted life years (DALYs). In non-agricultural domains such as malaria control, we might instead be comparing a GPM programme to investments in habitat control (e.g. applying insecticides against larvae) or insecticide-treated bednet distribution programmes.

For example, Fig. 6.4 below shows the synthesis of a large-scale cost-effectiveness of health interventions in developing countries (to address a variety of diseases). A 'grand' health intervention could be fashioned to seek the greatest gain in DALYs for a fixed budget. This figure can be used to prioritize such a programme. Begin by maximally funding the 'cheapest' intervention in the figure, i.e. the lowest expenditure per DALY averted (in Fig. 6.4: hygiene and sanitation to prevent diarrhoeal disease). Then use the remaining budget to maximally fund the next cheapest intervention ('emergency medical care') and so on. As yet (to our knowledge), it is not known in a public health context where traditional SIT or newer GPM approaches fit along this curve. Nor have such cost-effectiveness curves, including SIT and GPM, been produced in general terms for agricultural pest control (e.g. in terms of cross-pest reductions in yield loss). This highlights a useful area for future broad economic evaluations and syntheses of GPM.

Economic efficiency also implies that GPM (or any area-wide control measure) should account for how pest control decisions of individual growers might by impacted by an area-wide GPM programme. Recall in our model above that pest damages to individual growers are given by $d_i(P_t)$. Let us expand this function to include some individual control measure x_i (e.g. insect repellants or protective physical barriers) with pest damages now given by $d_i(P_t,x_i)$ and assuming a unit cost of q for x. This control measure x_i, by entering directly into the damage function $d_i(\cdot)$, is only assumed here to abate the grower's pest damage directly, and not to have any feedbacks into area-wide dynamics of the pest population state P_t. Examples of such measures could include repellants or physical crop protection barriers.

How would a rational grower adjust their decision about such private efforts as overall pest densities changed, e.g. in response to GPM? The key to answering this question (for an economist) is understanding how the incremental incentives for private control, in this case via the marginal damage function $\frac{\partial d_i}{\partial x_i} < 0$, are altered by area-wide suppression, i.e. reductions in P_t. In general, we would expect that area-wide reductions in pest densities would limit the incremental damage reductions that could be attained from private control, implying $\frac{\partial^2 d_i}{\partial x_i \partial P_t} < 0$. Appendix 6.2 shows mathematically that when this is the case, and when growers are assumed to respond in an economically rational manner, area-wide suppression can be expected to crowd out individual-level damage mitigation. Such a feedback should be accounted for in the overall benefit–cost analysis. Such feedbacks could also be important in non-agricultural contexts. For example, when (or if) GPM malaria control programmes are implemented, managers would need to consider how households might re-evaluate whether to use bednets, as overall mosquito densities or the risks of disease are reduced (but not yet eliminated).

An important caveat of this conclusion, however, is the assumption that individual control x_i only prevents damage (e.g. repels pests) in the immediate area, but does not suppress the broader area-wide population, P_t. Feedbacks from widespread farm-level pesticide use have been well-documented (Hutchison *et al.*, 2010; Dively *et al.*, 2018). Although a complete analysis of feedbacks of x_i into P_t requires more advanced mathematical tools, when such feedbacks are present, it is likely that GPM could complement other individual-level suppression measures such as pesticidal control (e.g. the suppress-and-release strategy described above). In this case, it is possible that GPM could 'crowd

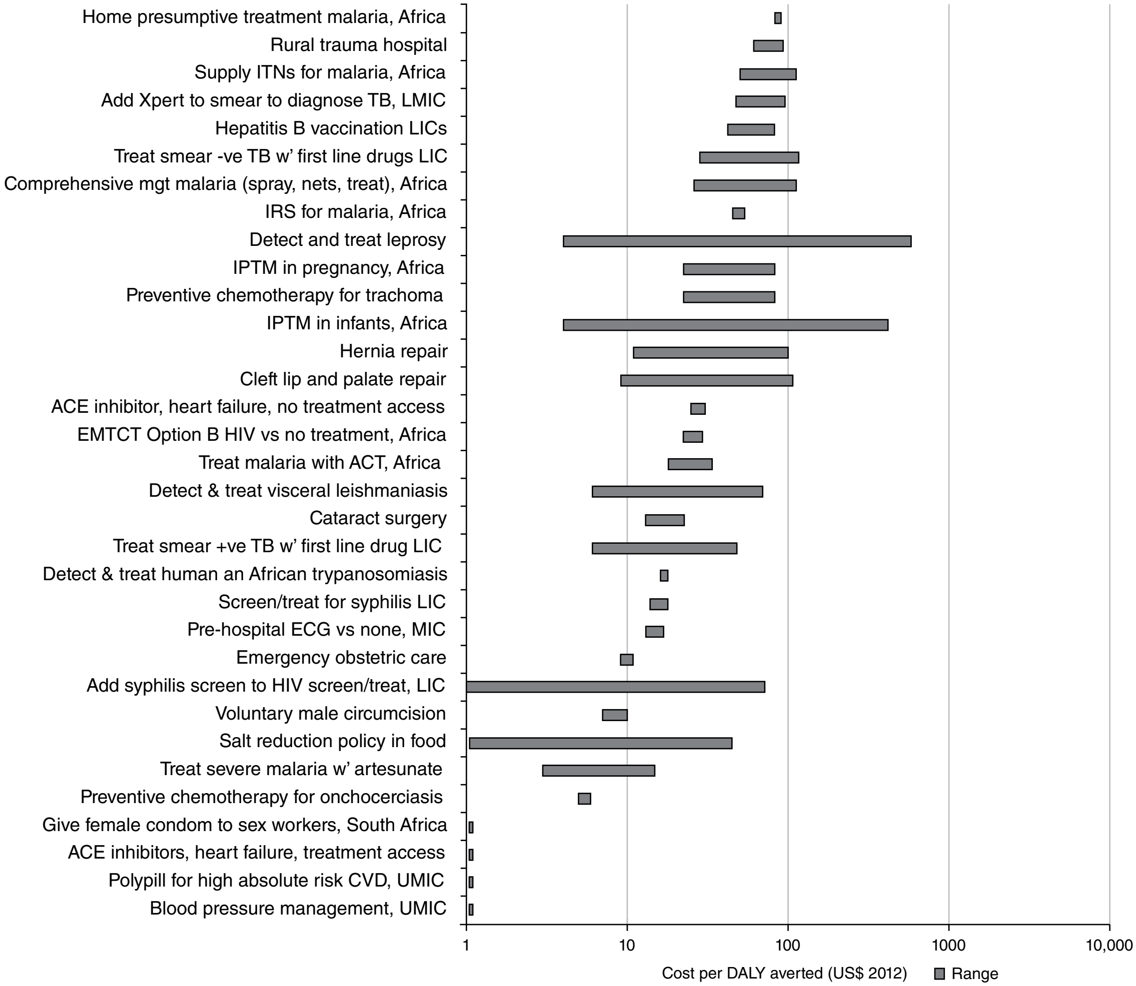

Fig. 6.4. Example cost-effectiveness analysis for interventions estimated to cost less than $100 per disability-adjusted life year (DALY) averted. Bars represent the ranges of recorded intervention cost-effectiveness (not statistical confidence). (From Horton *et al*., 2017.)

in' individual pest control measures; such an interaction has been alleged for example in an area-wide SIT Mediterranean fruit fly elimination programme in Croatia (Mumford, 2018). Anticipating complementary control measures from growers to the SIT programme could presumably have increased economic efficiency by reducing the facility capacity required to achieve a given level of pest reduction. This is obviously the case for forms of GPM *intended* to directly complement other control measures, for example in the mitigation of pesticide resistance emerging from individuals' pesticide use choices (Alphey and Bonsall, 2018).

Regardless of the *direction* of individual-level responses to GPM, the general point here is that tools from the behavioural and economic sciences should be used to *measure* these feedbacks, in order to improve benefit–cost analysis and decision making. As Epanchin-Niell (2017, p. 3344) observes for invasive species control in general, 'the management and spread of invasive species often depend largely on the choices of many decision-makers across the landscape, from landowners deciding whether to suppress invasions on their land to individuals making decisions that affect the transport of invaders to new locations'. The variety and uncertainty in these individual responses complicate the *ex-ante* economic evaluation of capital-intensive area-wide control measures such as SIT and GPM.

Uncertainty, irreversibility and option value

The review of GPM technologies above also should make clear another important feature of these approaches: *uncertainty*. Consideration of uncertainty includes how well these technologies perform at their intended objective and in the potential for unintended consequences. The primary uncertainty typically highlighted with conventional GPM and the related SIT concerns whether, and under what conditions, the intervention will be effective. The longer history of use of conventional SIT approaches has greatly increased our understanding of when these approaches are likely to be most effective (Klassen, 2005). For GPM much more uncertainty remains, although the biological literature reviewed at the beginning of this chapter discusses significant advances in our understanding.

Other uncertainties related to unintended consequences of a release are emphasized with self-perpetuating technologies like gene drives (or, to a lesser degree, *Wolbachia*-based biocontrol) due to greater potential for irreversible consequences. For example, a recent report on gene drives highlights the importance of conducting ecological risk assessment of gene drives, and of identifying and quantifying both the range of ecological consequences and their probabilities (NASEM, 2016). As this report notes (p. 110), 'because the goal of a gene drive modified organism is to spread, and possibly persist, in the environment, the necessary ecological risk assessment is more similar to that used for invasive species, than for environmental assessments of genetically engineered organisms'. That is, the potential *permanence* of gene drive impacts draws more attention to the risks of unintended consequences.

The simplest approach to incorporating uncertainty into benefit–cost analysis is the use of the 'expected NPV' (ENPV) criterion, in which the range of possible outcomes are enumerated, probabilities assigned to their occurrence, and the weighted sum of probabilities and outcome-specific NPV is calculated to obtain ENPV (Pearce *et al.*, 2006). The ENPV approach has two deficiencies for evaluation of GPM under uncertainty, one applies generally and one is of particular relevance to self-perpetuating technologies. The first deficiency is that the ENPV does not incorporate risk aversion. This means, for example, that one control plan that yielded very positive and very negative outcomes with equal probability would be judged no worse under the ENPV criterion than a control plan that yielded the same ENPV but with only one possible outcome about which we are certain. As a hypothetical example, a risky option might be a gene drive deployment that would be highly efficient and effective if it worked as intended, but with a significant risk of failing or imposing significant ecological damage if it malfunctioned. We might be comparing this to an alternative RIDL-based deployment requiring continual releases of modified organisms, which might carry lower risks than a gene drive but also would lead to lower NPV than under a gene drive's best-case scenario. If the ENPV were equal between the gene drive and RIDL systems, it would be reasonable for a risk-averse programme manager (or society as a whole) to prefer the lower-risk RIDL option.

There are standard methods from economic and decision theory for incorporating risk aversion in mathematical decision analysis models. These methods require quantifying, in a mathematically precise sense, the level of risk that the decision maker (or the stakeholder group or society as a whole) is willing to tolerate to achieve a higher expected payoff. Continuing the preceding paragraph's example, the degree of risk aversion could be measured by the minimum increase in ENPV that would be required to prefer the riskier gene drive option over a lower-risk (but also lower ENPV) RIDL or SIT alternative.

The second deficiency of the ENPV criterion for economically evaluating risk is the aforementioned potential for irreversible consequences of gene drives. Such irreversibilities cannot be properly accounted for in an ENPV criterion as it is usually formulated. Instead, economic evaluation of irreversible risks utilizes the concept of option value (see Mumford, 2001). The key insight from the option value concept is that for a potentially irreversible action there is benefit in waiting to learn more about potential consequences before taking action. In the context of gene drives, and in light of the NASEM (2016) report's recommendations, this could involve waiting for information about the ecological impacts of gene drive releases. This 'waiting to learn' aspect of option value is reminiscent of the Precautionary Principle, which is invoked in a variety of international policy frameworks for evaluating environmental and ecological impacts of new biotechnologies and invasive species. For example, the Convention on Biological Diversity (CBD) – the only international treaty to so far address the ecological risks of gene drives directly (CBD, 2017, 2018) – is based on the Precautionary Principle (UN, 1992). In fact, option value can be understood as an economically rigorous version of the Precautionary Principle (Gollier and Treich, 2003).

Figure 6.5 presents a stylized decision tree to explain how the concept of option value could be related to gene drives. Consider a two-period (t = 0, 1) decision model where in each period we face a simple binary decision of whether to release a gene drive. If we have already released the drive in t = 0, then the drive persists irreversibly into t = 1, and hence there is no further decision to be made. Suppose, for simplicity, the drive will either succeed with probability p or cause problems with probability $1 - p$. If it succeeds, we enjoy net benefits of 'success' of $v_S > 0$ in each period during which the gene drive is deployed. If it causes problems (i.e. backfires), we suffer negative net benefits from damages of $v_B < 0$ in each period of deployment. The uncertainty about whether the drive will succeed or lead to problems resolves at the end of the first period. Our decision in the first period is under uncertainty, whereas we have complete information in our second-period decision (remember, this model is stylized). A naïve application of the ENPV criterion in a benefit–cost analysis would be to deploy the drive in $t = 0$ if the ENPV of this deployment were positive, ignoring the potential to change our decision in the second period when we have more information. According to this naïve approach, we would therefore deploy if $pv_S + (1 - p)v_B > 0$. This can be rearranged to yield the rule that we deploy if:

$$-\frac{v_S}{v_B} > \frac{1-p}{p} \qquad \text{(Eqn 6.2)}$$

The left side of this relation is the positive ratio between the payoff from a successful deployment (v_S) and the damages ($-v_B > 0$) if it causes problems. The right side is the odds ratio between the probability of causing problems ($1 - p$) and the probability of success (p). For example, if there is equal probability of the drive succeeding or causing problems, then we only require the benefits of success to exceed the damages from causing problems in order to deploy the drive immediately. To clarify the discussion that follows, let us assume that Eqn 6.2 is true, i.e. that we would want to deploy the drive immediately based on the naïve ENPV criterion.

However, this naïve application of the ENPV criterion ignores the value from being able to react to better information in $t = 1$ if we do not deploy in $t = 0$. The decision tree constructed in Fig. 6.5 shows this logic. Suppose we have waited until the second period to decide whether to release the drive. Then, if at that point we learn the drive will succeed, we will obviously deploy it; because we delayed deployment until the second period, the NPV of this outcome (from the perspective of t = 0) is $\frac{v_s}{1+\delta}$, where $\delta > 0$ is the discount rate. The main loss from this outcome, in hindsight, is the foregone

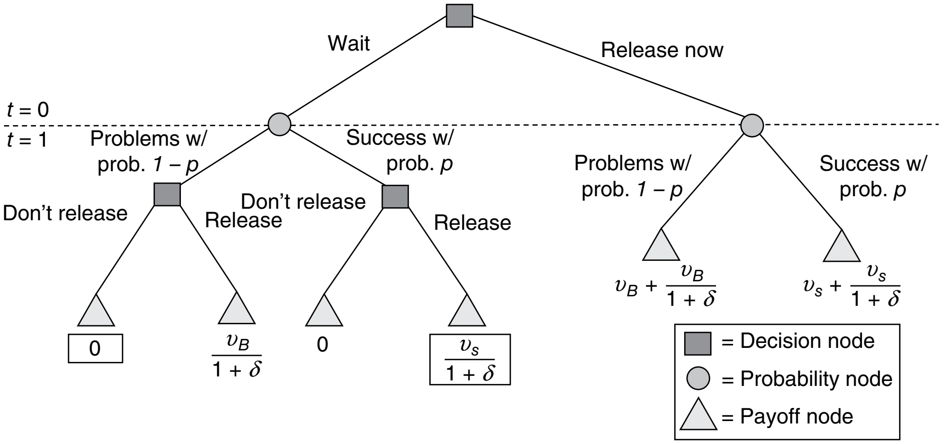

Fig. 6.5. The decision tree for an irreversible risk from release of a gene drive. The payoffs with boxes around them are the optimal ones for their respective second-period decision branch.

benefits v_S we could have had in $t = 0$ if we had known the drive would be successful. On the other hand, if we learn in $t = 1$ that the drive will cause problems with certainty, we will obviously decide not to deploy it, which leaves us with net benefits of zero. Therefore, our ENPV from waiting in $t = 0$, accounting for our optimizing behaviour in $t = 1$, is $p\frac{v_s}{1+\delta} + (1-p)0 = p\frac{v_s}{1+\delta}$. If instead we decide to deploy the drive in $t = 0$, we will enjoy a NPV of $v_s + \frac{v_s}{1+\delta}$ if the drive succeeds with probability p or suffer a NPV of $v_B + \frac{v_B}{1+\delta}$ if the drive causes problems with probability $1 - p$. In this example, the difference between net benefits of waiting until $t = 1$ to decide whether to deploy versus deploying in $t = 0$ (with the naïve ENPV criterion) amounts to what economists refer to as *quasi-option-value* (QOV):

$$\text{QOV} = \overbrace{p\frac{v_s}{1+\delta}}^{\substack{\text{ENPV from} \\ \text{waiting in } t\,=\,0}} - \overbrace{p\left[v_s + \frac{v_s}{1+\delta}\right] + (1-p)\left[v_B + \frac{v_B}{1+\delta}\right]}^{\text{ENPV from deploying in } t\,=\,0}$$

When QOV is positive, the expected value of waiting exceeds the value from deploying in $t = 0$; if it is negative then we should still deploy immediately. To compare this criterion to the naïve ENPV in Eqn 6.2, let us analyse what is required to have QOV < 0, i.e. for it still to be optimal to deploy immediately even after accounting for option value. This condition can be simplified algebraically to:

$$-\frac{v_s}{v_B} > \frac{1-p}{p}\left(\frac{2+\delta}{1+\delta}\right) \qquad \text{(Eqn 6.3)}$$

This criterion is almost the same as the naïve ENPV criterion in Eqn 6.2, except that the right side is multiplied by a factor related to the discount rate. We can quickly see this is a more conservative criterion to recommend immediate release. For example, if the probabilities of success and causing problems were equal ($p = 1 - p = 1/2$) and the discount rate were zero (meaning that next period's outcomes were weighted as much as today's), then the right side of equation (3) equals two, meaning that the benefits of a successful drive would have to be *twice* as large as the damages when a drive causes problems to warrant a deployment in $t = 0$. If instead the discount rate were infinite ($\delta \to \infty$), this would mean we should entirely disregard the second period. Then $(2 + \delta)/(1 + \delta) \to 1$, and the criterion in Eqn 6.3 reduces to the naïve ENPV criterion in Eqn 6.2: this is obvious, since if the future has no value, there can be no value to waiting to learn about it.

In addition to this decision tree being useful to consider unintended consequences such as permanent ecological risks, this general model is also appropriate for analysing a decision about whether to incur the sunk cost of building a GPM operation when there is uncertainty about a GPM technology's effectiveness. In this context, we could define $C > 0$ as the cost of the facility construction, and $B > 0$ as the potential recurring net benefits per period in the best-case scenario yielded with probability p, and zero benefits yielded with probability $1 - p$. If we deploy in $t = 0$, then ENPV is $pB\left(1+\frac{1}{1+\delta}\right)-C$. If we instead wait until $t = 1$ to learn (with certainty, in this simple model) whether the technology will actually function, then we deploy only in the best-case scenario, yielding an ENPV of waiting in $t = 0$ of $\frac{p}{1+\delta}(B-C)$. Then the QOV in this case is $\frac{p}{1+\delta}(B-C) - \left[pB\left(1+\frac{1}{1+\delta}\right)-C\right] = -pB + \left[1-\frac{p}{1+\delta}\right]C$. As with the previous example, this QOV can be rearranged to yield a threshold factor $\left(\frac{1}{p}-\frac{1}{1+\delta}\right)$ above which best-case benefits B have to exceed costs C in order for it to be optimal to undertake facility construction today, foregoing the benefits of learning.

For both of the above examples, there are many assumptions in this highly simplified option value model, but two important ones for the purposes of our discussion are (i) that deployment of the gene drive (or another self-perpetuating form of GPM) is in fact irreversible, and (ii) that information passively arrives to us in $t = 1$ so that we know by that point whether the drive will succeed or backfire. Assumption i, in the context of the first example, raises the issue of whether 'reversal drives' can be created to mitigate a problem-causing gene drive, a topic of recent scientific interest (Vella *et al.*, 2017). However, there is still significant uncertainty as to the performance of such reversal drives, so the potential for lasting impacts of a gene drive release remains a salient concern. Assumption ii omits the possibility that active acquisition of information on gene drive risks might be required to resolve the uncertainty, either about ecological risk in the first example or drive effectiveness in the second example. In particular, the ecological risk assessments of gene drives recommended by NASEM (2016) likely involve non-negligible resource investments, at least if they are to provide actionable information. In the case where other information about the deployment must be acquired actively, at cost, a key decision becomes whether (and how much) to invest in acquisition of this information. Another, related decision tool, the 'value of information', can be calculated to inform this choice. Value of information analysis has been applied, for example, in the context of malaria control to assess how reducing scientific uncertainty in our understanding of insecticide resistance can help improve vector control (Kim *et al.*, 2016; Gould *et al.*, 2018), and in decision making based on economic thresholds (Onstad *et al.*, Chapter 7).

GPM as a Public Good (or Bad)

As with any area-wide form of pest control, GPM will always to some extent affect parties who did not invest in – or are even opposed to – its deployment. This poses questions about whether individual incentives to invest in GPM align with the aggregate benefits and costs to stakeholders as a whole. Potential misalignments have practical implications for whether GPM would remain a primarily publicly (or quasi-publicly) funded enterprise, or instead could be expected to be partially or substantially funded by private actors.

Misalignments between individual incentives and aggregate outcomes can create positive and negative spillovers (sometimes simultaneously), depending on the specific GPM technology. Positive spillovers can arise from the local (or global) *public good* of area-wide (or world-wide) pest suppression. In economics, the defining characteristic of public goods is their *non-excludability*. While one party or group may undertake the effort at suppressing the pest over an area, they cannot exclude other parties in that area from enjoying the benefits of reduced damages over that area. Such positive spillovers have been well documented. For example, Hutchison *et al.* (2010) show that 60% of the benefits of European corn borer reductions in the US Midwest owing to the large-scale use of Bt maize accrued to growers of *non*-Bt maize. Dively *et al.* (2018) also document significant benefits in terms of reduced insecticide spraying among vegetable growers due to regional adoption of Bt field maize in the eastern US. From an economic perspective, these spillover benefits to some extent enable non-Bt growers to 'free-ride' on neighbours who used this technology.

This same logic can be seen to an even starker degree with more monolithic area-wide control programmes such as GPM, SIT and biological control. We can see this incentive to free-ride by returning to the simple intertemporal decision model in Equation 6.1 above, in which we earlier sought GPM programs that minimized NPV over a group of growers $i = 1, \dots, N$. For a GPM facility of scale k used to carry an otherwise optimal release schedule $\boldsymbol{r}^*(k)$, we can denote the resulting area-wide pest densities over time as P_t^k for each period k, and the resulting damages to grower i as $d_i\left[P_t^k\right]$, the NPV of which we can write simply as $D_i(k) > \sum_t \frac{d_i\left[P_t^k\right]}{(1+\delta)^t}$. Meanwhile, the NPV of recurring and fixed costs can be combined into the term $\mathbb{C}(k) > \sum_t \frac{c\left[r_t^*(k), k\right]}{(1+\delta)^t} + C(k)$. Using this notation, the NPV of damages and costs in equation (1) can be rewritten as:

$$\Sigma_i D_i(k) + \mathbb{C}(k) \qquad \text{(Eqn. 6.4)}$$

Equation 6.4 makes clear the key public goods aspect of area-wide GPM. Suppose a grower j was considering privately undertaking a GPM programme and wanted to determine the optimal level of investment that would be most efficient for them personally. Without any other contributors to the programme, they would bear the full cost $\mathbb{C}(k)$, but would only enjoy their portion of the benefits $D_j(k)$ and would ignore benefits to others $\Sigma_{i\neq j} D_i(k^o)$. They would therefore seek a capacity k^o that minimized their private NPV of pest damages and programme costs: $D_j(k^o) + \mathbb{C}(k^o)$. Because of the non-excludability of area-wide pest suppression, all the non-contributors to the project, meanwhile, would enjoy lower damages of $D_j(k^o) < D_j(0)$ at no cost to themselves.

The logic of this story implies a strong incentive for stakeholders expecting relatively fewer benefits from the programme not to contribute and to free-ride on the contributions of those who expect to gain most, resulting in some lower level of GPM below the socially efficient level k^* that optimizes the aggregate NPV in Eqn 6.1. In fact, because of the S-shaped benefits curve we derived previously in this chapter – with almost-zero benefits at capacity levels below the release threshold – in many cases we would expect that no individual grower would find it in their interest to carry out a GPM programme. This is why previous economic analyses of GPM and SIT have tended to be pessimistic about how much development of this technology we might expect in the private sector without the influx of public or quasi-public (i.e. growers' association) funds (Barnes, 2007). At the very least, as has been similarly seen in other area-wide control programmes (Singerman *et al.*, 2017), coordination among growers to muster the resources is required to solve the public goods dilemma inherent in such ventures.

These limitations to private sector involvement are likely to be even greater with gene drives and other self-sustaining GPM technologies (Brown, 2017; Gutzmann *et al*., 2017). The larger spatial scope and more permanent impacts promised by these technologies pose even more questions about how much the private sector could profit from selling such technologies in the absence of government sponsorship or tenders. If a set of discrete, one-off releases of gene drive mosquitoes or fruit flies are able to eliminate them permanently in an entire country or even globally, how could a private firm providing such a service capture profits commensurate with the scale of total benefits (as well the costs and risks) from such a programme?

That is not to say there are no commercial opportunities for GPM services. As Bassi *et al*. (2007) describe in detail for traditional Mediterranean fruit fly SIT programmes, there are numerous opportunities for the private sector to tender services in MRR operations – from insect modification, rearing, transportation, release and monitoring. And in-depth business plans have been created to stimulate private sector involvement in these ventures (Quinlan *et al*., 2008). But government funding (e.g. US Department of Agriculture's funding of SIT programmes for New World screwworm and pink bollworm, among others) or quasi-public funding (e.g. the California Cherry Board's funding to develop a gene drive for spotted wing drosophila, Regalado, 2017) will likely remain essential for GPM to be a viable option in area-wide IPM programmes.

Negative spillovers may also exist in GPM technologies that misalign private incentives and the public interest in the opposite direction: an overinclination to deploy these technologies. For example, suppose a growers' association and a technology developer identify a potentially profitable form of agricultural GPM but one that imposes substantial ecological – but non-agricultural – risk, e.g. the extinction of a native species of no agricultural value. This situation would give rise to what economists refer to as *negative externalities*, whereby the parties responsible for the decision to deploy would have no intrinsic economic incentive to consider these risks and are too prone to deploy the technology without proper controls, monitoring or mitigation options. Typical prescriptions for addressing this market failure are either government regulation, environmental laws that hold the deployers liable for ecological damages or (as economists tend to prefer) a direct incentive to internalize these risks in their business decisions. Such incentives could include taxes on deployment of risky technologies commensurate with their risk or subsidies for safer technologies commensurate with that safety; in theory, either the tax or the subsidy (or a mixture of the two) can yield equivalent economic efficiency. As with the public goods dilemma posed above, the potential for such externalities is likely greater in the case of gene drives and other self-sustaining technologies (Mitchell *et al*., 2018).

Conclusions

In this chapter we have reviewed existing and proposed forms of GPM and discussed some interactions with other forms of pest control through the lens of economic efficiency. We also discussed what might be expected in the economic behaviours of different agents who stand to gain more or less from use of this technology. A key conclusion from this discussion is that the thresholds required for modified insect releases to achieve their intended impacts have a wide variety of implications for the economics of GPM and its interactions with other forms of pest control. These thresholds are critical in determining the shape of damage reduction curve as a function of different GPM facility release capacities, and hence are key to determining economically efficient facility capacities. The uncertainty remaining as to how large or small these thresholds are (particularly in self-propagating forms of GPM), combined with the public good of the technologies' area-wide pest reductions, calls into question the economic viability of these tools, particularly in contexts where the benefits of the pest (or vector) reduction are non-monetary such as in malaria control. Consequently, reducing uncertainty in these release thresholds and at the same time facilitating cooperative and responsible technology development among stakeholders at appropriate scales are likely the keys to making GPM an economically attractive component of area-wide IPM. While the above conclusions have all previously been recognized for SIT programmes, they appear to be only magnified in the context of newer, gene drive forms of GPM.

Gene drives appear to raise the stakes of GPM deployment in others ways. Because of the significantly larger spatial scales and more permanent population modifications affected by these technologies, more attention appears to have been drawn to unintended ecological effects of deployment, as compared with more conventional GPM.

As has been noted elsewhere, this brings gene drives closer to classical biocontrol (where ecological impacts are of primary concern) than traditional GPM and the SIT (Brown, 2017). These conclusions take the question about whether and how self-propagating forms of GPM should be deployed beyond the realm of economics (Mitchell *et al*., 2018). For an intentionally invasive genetic engineering technology with potentially global impacts, the relevant set of affected parties becomes vast (Brown *et al*., 2018). As a consequence, careful discussions are necessary to clarify which intra- and international institutions have authority and influence in governing their use (Burgess *et al*. 2018; Stirling *et al*., 2018; Turner *et al*., 2018).

Appendix 6.1: Regression Analysis of SIT Fixed Costs

To justify the GPM facility cost function as a power-law (a.k.a. log-linear) form $C(k) = \alpha k^{\beta}$, we present a statistical analysis of the data described in the chapter. We argue that this power function form is supported by the available data and provide statistical evidence for the claim we make about increasing returns to scale in facility constriction, i.e. $\beta < 1$.

To test the posited power-law relation, we estimate a Box-Cox regression model:

$$\frac{C^{\lambda}-1}{\lambda} = A + \beta\frac{k^{\lambda}-1}{\lambda} + \epsilon \qquad \text{(Eqn A6.1)}$$

where A, B are regression coefficients to be estimated, λ is the Box-Cox transformation parameter and ε is unobserved regression error assumed to be normally distributed. When $\lambda = 1$, then Eqn A6.1 reduces to a linear regression model. When $\lambda = -1$, then Eqn A6.1 reduces to an inverse-linear regression model. When $\lambda \to 0$, then $\lim_{\lambda\to 0}\frac{x^{\lambda}-1}{\lambda} = \log x$ for any $x > 0$, so that Eqn A6.1 in this case reduces to $\log C = A + \beta \log k$. Taking the exponential of both sides, yields $C = \exp(A + \varepsilon) \cdot k^{\beta}$, and setting $\alpha := \exp A$ yields the posited power-law relation with the same parameters as in Fig. 6.1. We estimate the Box-Cox regression (Eqn A6.1) using bootstrapped errors with 500 replications to obtain the standard error of the estimate $\hat{\lambda}$. We obtain a point estimate of $\hat{\lambda} = -0.0666$. A test of the null hypothesis that the functional form is linear ($\lambda = 1$) or inverse linear ($\lambda = -1$) using a likelihood ratio (LR) test yields p values <1e-12, whereas a test of the null of a log-linear function form ($\lambda = 0$) yields p value = 0.479. Therefore (under the assumption of normally distributed unobserved errors ϵ), there appears to be strong evidence in favour of the power-law model (although statistically *accepting* the null hypothesis would be a more stringent test).

Therefore, assuming $\lambda = 1$ in Eqn A6.1, we then estimate the regression equation:

$$\log C = A + \beta \log k + \epsilon \qquad \text{(Eqn A6.2)}$$

where the parameters and variables are as before, but we no longer require ϵ to be normally distributed to obtain consistent estimates of β. Because 11 of the 17 observations in this dataset are Mediterranean fruit fly (Medfly) rearing facilities, we also estimate versions of Eqn A6.2 that allow A and β to vary according to whether the observation corresponds to a Medfly facility. The results are shown in Table A6.1 below. The key coefficients of interest are those corresponding to log(facility capacity): these are the β's in Eqn A6.2. The simplest regression in column (1) corresponds to the solid regression line in Fig. 6.1. The non-Medfly-specific coefficients in column (4) correspond to a regression fitted to only the non-Medfly-specific observations.

The key result from this statistical analysis is that we can statistically reject the null hypothesis of increasing marginal costs for Medfly facilities, but not for non-Medfly facilities. Notably, the estimated β's for non-Medfly facilities in (3) and (4) are *greater* than one, which would imply increasing marginal costs. However, the 95% confidence intervals for these non-Medfly β's are (0.58, 1.83) and (0.04, 2.65) for columns (3) and (4), respectively, so we clearly cannot statistically reject $\beta \le 1$ (i.e. decreasing marginal costs, economies of scale). With only six observations of non-Medfly facilities, we cannot say much statistically about facility costs.

Appendix 2: Bio-economic Analysis of Grower Behaviour Interactions with GPM

The net costs to individual i are $d_i(P_t, x_i) + q_i x_i$. If damages $d_i(\cdot)$ are convex in x_i, then the first-order condition $\frac{\partial d_i}{\partial x_i} = -q_i$ determines grower i's optimal individual level of control, which is a function of area-wide pest density, $x_i^*(P_t)$. Totally differentiating the first-order condition and rearranging implies that:

$$\frac{dx_i^*}{dP_t} = -\frac{\overbrace{\partial^2 d_i \big/ \partial x_i \partial P_t}^{(-)}}{\underbrace{\partial^2 d_i \big/ \partial x_i^2}_{(+)}} > 0$$

Table A6.1. Ordinary least squares regression coefficient estimates for facility costs.

Dependent variable: log(facility costs)	(1)	(2)	(3)	(4)
log (facility capacity)[a]	0.676***	0.844		
	(0.213)	(0.222)		
X Non-medfly facility			1.204	1.341
			(0.295)	(0.615)
X Medfly facility			0.710*	0.622***
			(0.166)	(0.0784)
Constant	−1.506		−2.248**	
	(1.069)		(0.908)	
Non-medfly facility (6 observations)		−1.127		−2.817
		(1.274)		(2.421)
Medfly facility (11 observations)		−2.848**		−1.759***
		(1.065)		(0.469)
Observations	17	17	17	17
R-squared	0.517	0.823	0.798	0.887

Jackknife standard errors in parentheses. Statistical significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. 'Medfly' = Mediterranean fruit fly.
[a] Statistical significance for this variable, and its interactions with (non-)medfly facilities, are reported for one-sided test of the null of increasing marginal costs, i.e. $\beta \geq 1$.

Because $d_i(\cdot)$ is assumed convex in x_i, the denominator on the right-hand-side of the above is positive. And the main text motivates the assumption that the numerator of the above is negative. As a consequence, the above equation implies that increases (decreases) in area-wide pest *densities* P_t would lead the economically rational grower to increase (decrease) their optimal private level of damage mitigation x_i^*.

To see how this behavioural response translates into overall benefits from an area-wide suppression effort, substitute this grower-level control function $x_i^*(P_t)$ back into the grower's damage function, i.e. $d_i[P_t, x_i^*(P_t)]$, and then take the derivative of this composite function in P_t using the Chain Rule from calculus we get:

$$\frac{d}{dP_t}\{d_i[P_t, x_i^*(P_t)]\} = \underbrace{\frac{\partial d_i}{\partial P_t}}_{(+)} + \overbrace{\underbrace{\frac{\partial d_i}{\partial x_i}}_{(-)}\underbrace{\frac{dx_i^*}{dP_t}}_{(+)}}^{(-)}$$

This allows us to compare the marginal benefits (damage reductions) ignoring v. accounting for adaptive grower responses. The last term in the above equation, being negative, suggests an attenuation of GPM's pest reduction benefits when properly accounting for grower behavioural responses.

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7

Economic Thresholds and Sampling in Integrated Pest Management

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When farmers see insects and crop damage during a season, they usually think of insecticides as the first option for pest control. When entomologists and pest management consultants observe the same, they typically think of sampling and economic thresholds (ET). These thoughts may be a consequence of the tendency for integrated pest management (IPM) courses to cover economics of decision making only in the context of insecticide use based on economic thresholds. However, as Chapter 1 and other chapters in this book indicate, other choices and other economic analyses can be made by farmers and their consultants. But of all proposed rules for economic decision making in IPM, none has been as pervasive and influential as the concepts of the economic injury level (EIL) and ET proposed by Stern *et al.* (1959).

Stern *et al.* (1959) knew that most insect control after 1945 was dependent on chemical insecticides, and they also understood the problems of extensive insecticide use, which were highlighted by Rachel Carson (1962) in *Silent Spring*. Stern *et al.* (1959) emphasized the need to only use insecticides when the damage caused by uncontrolled populations would exceed the cost of controlling them. They essentially declared that crop consultants and farmers should measure their pest populations before every decision to treat the crops.

As the rest of this chapter demonstrates, these two simple ideas, (i) count pests and (ii) compare predicted costs to predicted benefits, involve many complications and limitations that make sampling and ETs easier to discuss than implement. One obvious difficulty is prediction. Stakeholders must predict future pest populations and the damage that they cause, because it is the preventable damage and loss in harvested crop that is compared with the estimated cost of control. The other less obvious, but all too common, problem is that economic thresholds are useless without proper sampling, and proper sampling has not been easy to define or implement.

We have two goals for this chapter. First, summarize and highlight the techniques that have been developed over the past 40 years to facilitate and improve the calculation of ETs. Second, emphasize the need to develop cost-effective sampling methods that can support the use of ETs.

Basic Concepts and Techniques

Although Stern *et al.* (1959) created the concept, Headley (1972) and Southwood and Norton (1973) defined the EIL as the density at which the cost of additional control equals the economic loss prevented by implementing the control tactic. This was necessary to eliminate EIL/ET ambiguity and to make the definition more rigorous. Here, we define the ET as a current pest density that represents a future population, the control of which will prevent economic loss equal to the cost of implementing the control tactic (Onstad, 1987).

Onstad (1987) created general formulae for ETs that extended the ideas that had been developed in

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the 1950s to the 1970s. Onstad's perspective is based on the factors highlighted in Fig. 7.1. The main feature of this perspective is that it considers all of the time during which the pest can possibly occur on the farm. In addition, the system is considered dynamic. The ET can be lower or higher than the EIL depending upon whether the population is increasing or decreasing. Sampling, decision making and implementation of control tactics are not restricted to a given period. Two of many possible scenarios for decision making are presented in Fig. 7.2. Sampling and control might be performed while the pest population is increasing (Fig. 7.2a) or while it is decreasing (Fig. 7.2b). In both cases, control tactics are implemented only if the estimated density exceeds the ET (not shown) for that particular time. When control is justified, density *g* equals the EIL and density *f* equals the ET. In Fig. 7.2a, the EIL is greater than the ET, but in Fig. 7.2b the ET is a higher density than the EIL. A density at any time (a point on the curve) can be related to the total density of the stage or population using knowledge about population dynamics.

Control measures are evaluated and the EILs and ETs are calculated by comparing the damage (economic loss) resulting from preventable injury (a function of pest-days in Fig. 7.2) with the cost of control. When the preventable damage equals the cost of control, the estimated density equals the ET. Injury occurring before sampling cannot be reduced and the resulting damage (yield loss or lower quality) cannot be prevented; therefore, past injury should not be included in the decision.

Figure 7.2 suggests that sampling and control tactics are usually applied to injurious stages of a pest's life cycle. This is not always the case, as Fig. 7.3 demonstrates. The first set of densities (first triangle) represents an egg stage or other non-injurious age class, and the second set represents a subsequent stage that causes injury (shading under the lines). In Fig. 7.3, control tactics are put into effect, if necessary, against the first stage. It would also be possible in some situations to sample the first stage and apply the control against the second stage. In either case, the decision is based on a comparison of the expected preventable injury and damage with the cost of control. Unpreventable injury is not included.

Another major aspect of this perspective is the realization that every point in time has an EIL and ET (Fig. 7.1). For each life stage, the EIL (and ET) changes over time. For each time, there is a different EIL for each life stage. Because sampling protocols are usually restricted to a single stage, a dynamic EIL is the density threshold for a given life stage of a pest that changes over time. Over time, the same control tactic will be associated with a number of thresholds (e.g. $EIL_{t=1}$, $EIL_{t=2}$, $EIL_{t=3}$). Many authors have developed a different EIL or ET for a pest at each of several growth stages of a crop.

The choices for the timing of sampling and control may seem chaotic in Fig. 7.1, but it is a realistic

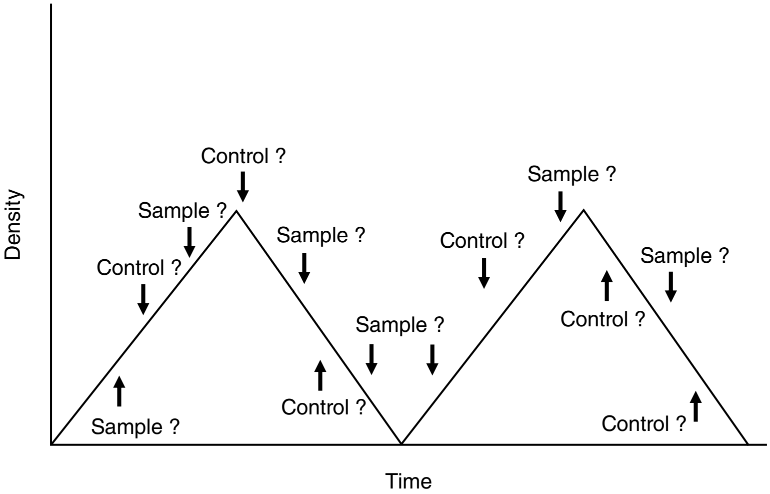

Fig. 7.1. Unlimited options for the timing of decision making in IPM. (Reprinted from Onstad, D.W. (1987) *Journal of Economic Entomology* 80, 297–303 with permission from Entomological Society of America.)

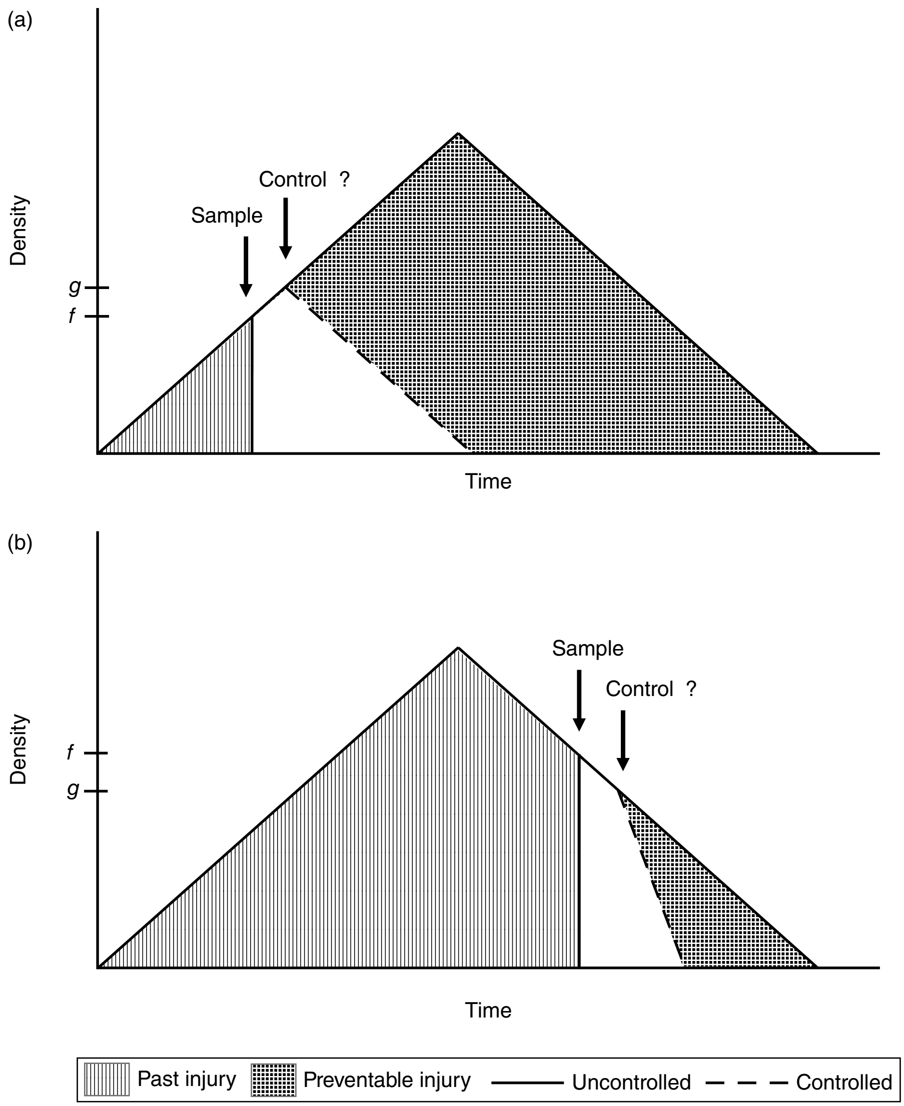

Fig. 7.2. Perspective of pest control decision making in which data collected at one point in time are viewed as part of a dynamic system with a past, present and future. Sampling occurs when densities are (a) increasing or (b) decreasing. The density *f* represents the sampled density and *g* is the pest density at time of control. (Reprinted from Onstad, D.W. (1987) *Journal of Economic Entomology* 80, 297–303 with permission from Entomological Society of America.)

picture of the possibilities that exist before the creation of a more restrictive decision making policy. The decision maker must choose the sampling time, the life stage that is sampled and the time for implementing control tactics. Norton *et al.* (1983) noted that ticks (*Boophilus microplus*) on cattle in Australia can be managed in various seasons and generations and that the threshold for control will be different in each season of sampling. Figure 7.1 also suggests that contingency plans should be available for farmers who are unable to follow the best plan, especially with regard to sampling. The same concepts apply to pests with multiple generations in a season and to those that can be regulated over several years. For example, Torell *et al.* (1989) included the benefits in future years when evaluating

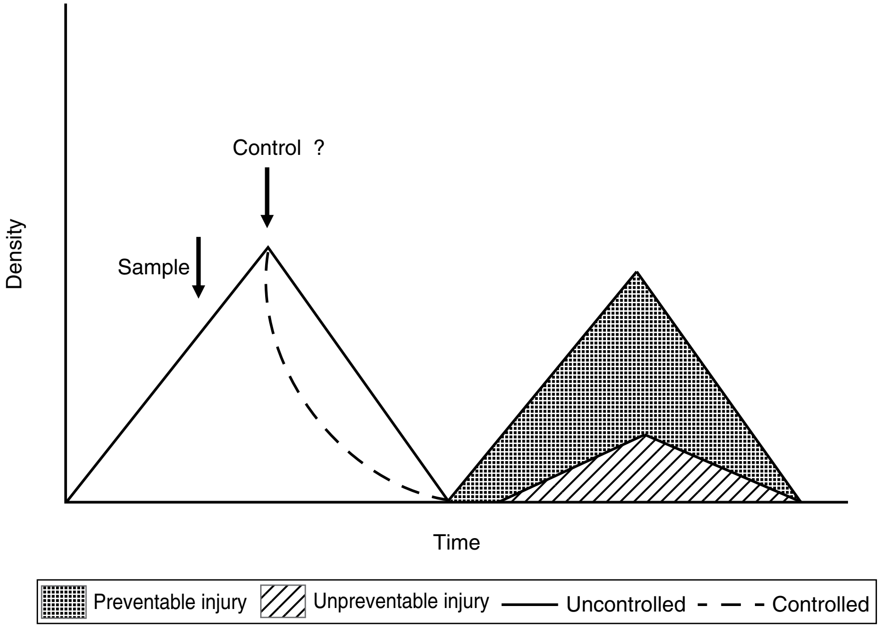

Fig. 7.3. Decision making when an injurious life stage or generation is preceded by a non-injurious population. (Reprinted from Onstad, D.W. (1987) *Journal of Economic Entomology* 80, 297–303 with permission from Entomological Society of America.)

EILs for grasshoppers (Acrididae) on rangeland in the United States. The rangeland is used for forage for livestock. Controlling the grasshoppers in 1 year can provide future benefits, which Torell *et al.* discounted according to typical economic assumptions to determine the net present value. Note that decisions regarding control of forest pests have sometimes considered benefits over multiple years, too.

Note that IPM activities can occur on a variety of schedules. Sampling, decision making and implementation of control tactics occur over chronological or physiological time (i.e. growth stage). Events not involving pest management often force the decision maker to be flexible in implementing management activities over time. The ET was conceived by Stern *et al.* (1959) because sampling and decision making often occur sometime before control tactics are implemented. Use of an ET focuses attention on the time of sampling, whereas calculation of EIL tends to emphasize time of control implementation.

Economic loss follows from two processes: one purely biological and the other economic. Injury is the physical or physiological effect of the pest on the plant or animal. The economic loss resulting from injury was defined by Norton (1976) as damage. With this definition, damage is also the economic injury described by Stern *et al.* (1959). A density/damage function relates the density of one or more life stages (or species) to the economic loss in crop or livestock yield and quality. This function can consist of several parts, such as a density/injury function plus an injury/damage function (Pedigo *et al.*, 1986). Yield and price are usually included in the damage function.

Onstad (1987) created the following equation to help with calculation of EILs and ETs. Based on the work of Southwood and Norton (1973), the difference between costs with and without control must equal the difference in resulting benefits at the EIL.

$$\begin{aligned} C(ht*) - C(ht) = Y\left[dt\{s(ht*)\}\right] \\ \times P\left[dt\{s(ht*)\}\right] - Y\left[dt\{s(ht)\}\right] \\ \times P\left[dt\{s(ht)\}\right] \end{aligned}$$

Where C is cost, Y is yield of harvestable crop, P is price based on quality, h is the control tactic with h^* the tactic being evaluated, d is pest density and s is control based survival. The EIL is found by solving the equation for d. Density d is a function of survival, both of which may be dynamic. Yield and price are both functions of the future densities. We typically expect that the cost with the new tactic is larger than the cost without it. And the benefits (Y × P) with the new tactic are greater than or equal to those without. This equation also allows comparison of two different control tactics, not just the one tactic versus an uncontrolled case.

Onstad (1987) developed formulae for both linear and quadratic density-damage functions (the functions for Y and P above). However, as the complexities increase, full-scale mathematical models may be needed (Szmedra *et al*., 1990). Note that the ETs do not need to be derived from EILs – they can be calculated directly (Onstad, 1987).

Control is time-dependent management of a pest population. A control tactic consists of the material, equipment and method used to remove, repel or kill the population. A control tactic can involve cultural, chemical or biological methods. Mortality due to control is a function of weather and other environmental factors, pest susceptibility, control tactic and level of application (Barrigossi *et al*., 2003; Paula-Moraes *et al*., 2013). Cost of control is a function of the control tactic and the time and labour involved in putting it into effect. Costs can also include the damage to plants and animals caused by use of control tactics such as pesticides. (In the section below, we highlight the cost (and value) of sampling.)

The techniques described above take a deterministic approach to prediction. The assumption is that all situations in the future application of the economic threshold will have no uncertainty, or at least that any uncertainty is not worth dealing with. A few authors have incorporated uncertainty into the process to account for the true stochastic nature of pest and crop management (Plant, 1986; Peterson and Hunt, 2003). In a section below, we discuss the uncertainty in the sampling of pest density.

Sampling in IPM

Sampling is often considered a necessity but is rarely evaluated in the wider context of decision making (Binns and Nyrop, 1992). If sampling costs too much relative to the possible damage caused by the pest, then farmers will need a different approach to economic decision making, or they will simply take the easiest, risk-averse technique for pest management, which typically means periodic insecticide use without regard to pest density (Leather and Atanasova, 2017; Ramsden *et al*., 2017).

Most control-based IPM programmes depend upon inexpensive and rapid determination of pest population levels (Kogan and Herzog, 1980; Herzog, 1985; Binns and Nyrop, 1992). However, sampling strategies depend upon several factors, including the species to be sampled, characteristics of the crop at the time of monitoring, as well as sampling costs and difficulties related to this process. Sampling of pests requires knowledge of their biology, preferred habitats and activity patterns, among other information.

Practical problems for farmers arise because different pests might require different sampling procedures, and because more than one pest can be present on the crops at the same time. However, because it is time-consuming, the use of different sampling methods will generally be rejected by growers. The time investment in insect sampling and the need for qualified workers are notoriously among the greatest constraints to be overcome in IPM. For example, several studies have shown that for insect pests that occur in soybean, as well as for the collection of their natural enemies, the beat cloth method is the most efficient and practical technique. However, soybean growers have complained about the difficulties of this method, such as being too time-consuming for large soybean areas, and a lack of workers trained in its execution. Because of these difficulties and the low price of chemicals, soybean growers re-adopted the ‘identify and spray’ strategy, which resulted in an enormous decline in soybean IPM worldwide (Bueno *et al*., 2011a). Furthermore, when we take for granted any knowledge derived from a few samples, we are ignoring the uncertainty surrounding this knowledge.

Some techniques provide an absolute estimate of the pest’s density in a field (Hillhouse and Pitre, 1974; Kogan and Pitre, 1980), but most methods estimate relative values or approximations of absolute values. According to Mayse *et al*. (1978), direct insect observation achieves higher fidelity and greater efficiency in relation to the number of species sampled, and is therefore an adequate approach for some species. However, the evaluation of sample points with relative estimates of pest populations is usually more appropriate (Kogan and Pitre, 1980) because, in a common field scenario, pest diagnosis and decisions must be made rapidly to avoid economic loss.

IPM is improved when a practical sampling method can be developed that is adequate for most pest species affecting a single crop. Therefore, sampling methods and other techniques are constantly revised to reduce costs and to enhance their practicality. A recent, promising approach to insect sampling is the use of aerial images (satellite or drone images). With the development of more powerful and cheaper cameras, this technology might become useful for insect monitoring in IPM with great ease, speed and at lower cost. However, the use of aerial images still needs further calibration and adjustment.

Sequential sampling balances sampling effort and reliability of abundance estimates, which are of fundamental importance for IPM decisions (Hodgson *et al.*, 2004). Based on the decision protocols for stink bugs in soybean proposed by Todd and Herzog (1980), a sequential sampling plan was developed and implemented in Argentina for *Nezara viridula* and *Piezodorus guildinii* (Trumper *et al.*, 2008). Costa *et al.* (1988) created a sequential sampling plan for stink bugs in large plantations of soybean using the beat cloth method. Costa (2009) constructed sequential sampling plans for *Diaphorina citri* nymphs and adults in citrus orchards.

Nyrop *et al.* (1999) published a philosophy and a technique that both solve some common problems for IPM practitioners and challenge the typical ideas about sampling insect pests. They strongly support the philosophy that we need good estimates of economic thresholds – what they call critical densities that signal the need for insect control. What is different is that Nyrop *et al.* (1999) clearly develop a technique that de-emphasizes precision in sampling and emphasizes the ability through sampling to directly determine whether the pest population is likely above the economic threshold or below it. This is the difference between estimation (conventional sampling) and classification of the population. For IPM decision making about control with insecticides, a technique is needed that allows entomologists to determine the number of samples that should be taken considering the probability of incorrect management decisions. The approach advocated by Nyrop *et al.* (1999) balances the cost of data collection with the likelihood of making an incorrect decision.

The Cost and Value of Sampling

Nyrop *et al.* (1986) explained how the value of sample information can be used to evaluate and construct decision rules for use in pest management. Their method is based on Bayes' principle of insufficient reason. Essentially, entomologists should realize that we have uncertain understanding about pest density, and therefore, a probability distribution should represent the pest densities in decision making. Thus, probabilities that are assigned to the possible pest densities indicate the relative likelihood that each of these densities is the true density.

Nyrop *et al.* (1986) emphasized four major steps. First, the IPM problem must be described with three components: (i) prior knowledge of the occurrence of pest densities expressed as a set of probability measures, (ii) a sample likelihood function that provides a probability measure for obtaining a sample estimate given any true pest density and (iii) the losses a farmer incurs when taking any pest control action when a particular pest density occurs. Second, before choosing an action, a decision maker may sample the pest population. Third, if sample information is collected, updated probabilities for the pest densities are computed using Bayes' theorem. Fourth, the optimal action to take is determined by calculating the expected loss for each action where the expected value is calculated with respect to the range of pest densities that may exist. The optimal action produces the lowest loss (including cost of sampling) compared with all other possible actions with or without sampling.

Nyrop *et al.* (1986) also described how decision theory can be used to determine the value of sample information. The value of the sample information is the expected loss of the optimal act *without* sampling minus the expected loss of the optimal act *with* sampling when the expected value in both cases is calculated with respect to the updated probability measures for the pest densities. For example, if the loss without sampling is $500/ha and the loss with sampling (including the cost of sampling) is $450/ha, then sampling or sample information has a $50/ha value.

What do we know about the pest's densities over time and space? A non-uniform prior probability distribution is useful when it is known that a pest most often occurs at either high or low densities over time and space. For example, if we know that over many seasons and over a large region, a pest tends to have many more instances of low densities (<100/m) than higher densities (>1000/m), an exponential function with higher frequencies for lower densities may be a reasonable prior probability distribution. A sample estimate for the true current density should be considered as representative of the true mean given our prior knowledge. If it is a very high estimate based on a single sample, we likely will give it a low probability of being true. With few samples, we give more weight to the value of the prior distribution. As the number of samples increases, we give more weight to the sample-based mean in our analysis and decision making. In instances when pest densities vary widely without a clear pattern, representing prior knowledge with a uniform distribution is most appropriate, since the sample data should be relied upon for assigning probabilities to the pest densities. A uniform distribution is often the most conservative with respect to sample size but also leads to higher sampling costs (Nyrop *et al.*, 1986).

It is likely that probabilities used to represent prior knowledge will change over time or as pest abundance is better understood on a regional basis. Therefore, through the use of decision theory, it may be found that sampling intensity can change over a growing season or that sampling may not even be worthwhile. Foster *et al.* (1986) showed that sampling for adult *Diabrotica barberi* and *D. virgifera virgifera* in the United States may not be worthwhile in fields under continuous maize (*Zea mays*) production. Nyrop *et al.* (1989) performed an economic analysis of the value of sampling information derived from a sequential sampling programme for *Acrolepiopsis assectella* in leek (*Allium ampeloprasum*) fields in The Netherlands. The parameters used for the analysis were crop yield and value, expected level of moth infestation, potential loss of value due to moth infestation, insecticide efficacy and sampling costs. Because insecticide application costs for this high-value crop were very low, Nyrop *et al.* (1989) concluded that (i) there was little economic difference between a sampling-based management plan and prophylactic application of insecticides, and (ii) development of a pest-density threshold linked to a sampling procedure will not reduce costs. They also concluded that, even though sampling would not significantly increase pest control costs, sampling would likely reduce insecticide use compared with a prophylactic treatment programme.

Nyrop *et al.* (1986) also discussed the relationship between sampling intensity and the estimated pest density at which a control action should be initiated. They referred to this density as the control decision threshold, which differs from an economic threshold in that it accounts for uncertainty in sampling and in cost of sampling. Nyrop *et al.* (1986) used a uniform distribution when evaluating the value of sample information and control decision thresholds for management of *Empoasca fabae* in alfalfa (*Medicago sativa*).

Obviously, to use the approaches developed by Nyrop and others, the basic cost of sampling must be known. Here we review some of the papers that have measured this cost, so that the techniques and effort required can be understood. Sampling can be instantaneous as when a person walks into a field and counts or captures the insects while walking. Or sampling can involve trapping to collect insects over a week or a month to determine a cumulative measure of the pest population.

Fernandes *et al.* (2010) evaluated the use of a trap to capture Cerambycidae in forest plantations in Brazil. Although most traps in forests use pheromones or light as the attractant, they used plastic bottles with ethanol, methanol and benzaldehyde to attract the wood-boring beetles. The traps were checked biweekly and required 1 min of labour per trap. Fernandes *et al.* (2010) determined the total cost of materials and labour per sample.

Ferrer and Hammig (2012) investigated the role of sampling in IPM for collard (*Brassica oleracea*) production in the United States. They compared conventional sampling to sequential sampling. Sequential sampling involves the use of categories of pest densities that indicate when sampling can be stopped and a decision made. They first showed that either approach can save money for collard growers. Then they determined that the cost savings were higher for sequential sampling because of lower sampling time and labour costs. This is similar to the analysis made by Gusmao *et al.* (2006) for the sequential sampling plan for *Bemisia tabaci* in tomato (*Solanum lycopersicum*) fields in Brazil.

Economic Thresholds for Multiple Species

The ultimate test of IPM is the management of multiple pest species that attack the same crop, if not more than one crop, in a landscape (Hammond, 1996). Two approaches have been taken to address part of this problem with EILs and ETs. One approach tries to combine several species into an EIL with one sample (one dimension). The other approach is multidimensional (Blackshaw, 1986). It accounts for different species by measuring them separately, but then uses formulae or models to determine how the knowledge of all the species should affect management. The former considers common injury and common capture during sampling; the latter only finds economic relationship through use of a more complex model. Onstad and Rabbinge (1985) developed multidimensional thresholds based on sampling both cereal aphids and a wheat disease caused by *Puccinia striiformis* in The Netherlands. They concluded that as the sampled estimates of the two types of pests increased, the threshold at which control action must be taken against each one decreases because of savings from simultaneous application of both insecticide and fungicide. Onstad and Shoemaker (1984) were able to develop multidimensional thresholds based on sampling of both the pest, *Hypera postica*, and a naturally occurring parasitoid in alfalfa in the United States. Giles *et al.* (2017) promoted the measurement of natural enemy and pest densities and use of a natural enemy threshold when making decisions about insecticide applications.

Combining species into one dimension is represented by the following investigations. Onstad and Rabbinge (1985) simply calculated dynamic one-dimensional EIL's for the management of aphids, *Sitobion avenae* and *Metopolophium dirhodum*, on several growth stages of winter wheat (*Triticum aestivum*) in The Netherlands. Johnston and Bishop (1987) considered two species of cereal aphids to be similar enough to develop one economic threshold for use in controlling both on spring-planted wheat in the United States. They also created ETs that changed as the wheat matured.

Larry Pedigo and his students were major proponents of conversion to one dimension (Pedigo *et al.*, 1986), especially for pests that occupy the same feeding niche and produce similar plant injuries (e.g. defoliation can be caused by different insects or pathogens). Similarities in plant physiological response to such injuries have been identified for a variety of pest species. This has substantial practical advantages because by integrating different pest species into a single injury guild, pest management programmes can be developed for the entire guild, as opposed to managing each pest species individually. Of course, for one ET to work for all species, the applied insecticide must control them with the same efficacy and sampling costs and precision must be similar.

Boote (1981) first defined injury guilds by emphasizing physiological responses of plants to specific injury types. He suggested five injury guilds: (i) fruit feeders, (ii) stand reducers, (iii) assimilate sappers, (iv) leaf-mass consumers and (v) turgor reducers. Pedigo *et al.* (1986) proposed the additional guild of a 'plant architectural modifier'. These authors suggested that EILs and ETs for multiple pest species could be developed for insects in the same injury guild on the same crop. Higley *et al.* (1993) added a seventh type to the injury guilds, and suggested several others as categories of physiological impact. They included, among others: leaf photosynthetic rate reduction, leaf senescence alteration, light reduction, assimilate removal and water balance disruption. The injury types coupled with the magnitude and duration of injury are important determinants of yield loss. Injury magnitude can be further divided into acute (short-term) and chronic (long-term) injuries with different impacts on crop yield (Peterson and Higley, 2001).

Hutchins *et al.* (1988) developed a technique that grouped insect-caused injuries based on the physiological response of plants. These authors defined injury in the standard units of 'injury equivalent' representing the total injury produced by a single pest over its entire lifespan. Using this method, Hutchins *et al.* (1988) grouped five defoliators and developed an EIL based on their insect-injury equivalents. Hunt *et al.* (2003) developed a multiple-species EIL for two beetles feeding on soybean.

Bueno *et al.* (2011b) proposed an insect-injury equivalent for five common caterpillar species in Brazilian soybean (*Glycine max*). A standard equivalent species, *Anticarsia gemmatalis*, provided the comparison for plant consumption. The insect-injury equivalent of *Spodoptera cosmioides* differed significantly from that of other species and was nearly twice as high as that of *A. gemmatalis*. Bueno *et al.* (2011b) concluded that the injury equivalent should be two for *S. cosmioides* and one for all other tested species (*Chrysodeixis includens*, *Spodoptera eridania*, *Spodotera frugiperda* and *A. gemmatalis*). The recommended ET for triggering insect control would be 20 insect equivalents per sample cloth (1-m soybean line), similar to the level proposed for other soybean defoliators (Hutchins *et al.*, 1988; Haile *et al.*, 1998). The injury equivalence system can sometimes be inconsistent because at high insect densities, competition can reduce injury rates per individual. This should be examined in future, multiple-species ETs, for example, by an appropriate adjustment based on the density-injury per individual function. Such a function could easily be developed as part of an interactive computer implementation of the multiple-species ET model (Hammond *et al*., 1979), greatly improving future ET recommendations in IPM.

Case Studies

In this section, we describe a variety of studies and projects in which thresholds have been calculated or used. Integration of tactics is always good news of interest to entomologists. Several studies highlighted below consider tactics other than or in addition to insecticide use. One obvious integration is that of host-plant resistance with insecticides (Ring *et al*., 1993; van den Berg *et al*., 1997). When natural biological control was considered by Coop and Berry (1986), they determined that the ET for insecticide use against a leaf-feeding pest on peppermint (*Mentha piperita*) was 34% higher than without biological control.

In some cropping systems, the effects of the pest and management on quality of the harvested products must be considered. Hutchison and Campbell (1994) measured sugar content during their investigation of an economic injury level for an aphid on sugarbeet (*Beta vulgaris*) in the United States. Even more interesting was the economic study by Sadof and Alexander (1993) in which they measured customers' reactions to the aesthetic quality of shrubs sold at a nursery in the US.

Maize IPM in the United States

Two studies 20 years apart drew the same conclusion about the value of sampling and use of ETs for managing *Diabrotica virgifera virgifera* on maize (*Zea mays*) in the United States (Foster *et al*., 1986; Crowder *et al*., 2006). Crowder *et al*. (2006) studied how ETs could be used to make decisions about planting transgenic insecticidal maize. The decisions are made after sampling of adult beetles at the end of the summer in the year prior to planting the maize fields. The ET for a given insecticide dose expressed in the plant is the adult density at which the costs of planting transgenic insecticidal maize in 100% of the maize fields the following season equalled the benefits of planting transgenic maize. If the threshold is not exceeded, no insecticidal maize is grown in the next year. They did not include the costs of sampling in their analysis, because they wanted to let the analysis show how much sampling would be worth to a farmer. Foster *et al*. (1986) used a similar approach to determine the usage of soil insecticides to control *D. virgifera virgifera*, which has one generation per year, but Foster *et al*. (1986) used a 1-year time horizon while Crowder *et al*. (2006) used a 15-year horizon that accounted for annualized net present value of management and the evolution of resistance by the pest.

Crowder *et al*. (2006) found that planting transgenic insecticidal crops based on sampling and ETs did not generally increase returns compared with planting transgenic maize every season. Large adult densities in refuges and subsequent dispersal into insecticidal maize fields caused populations to exceed the ETs in almost every year. This resulted in minimal differences between the sampling strategies and the strategies of planting insecticidal maize each season, because transgenic crops were planted nearly every season even when sampling was utilized. They also discovered that the use of sampling and ETs can slightly slow the evolution of resistance to transgenic insecticidal crops, because selection does not occur in years when transgenic crops are not planted. For continuous cropping of maize, Crowder *et al*. (2006) concluded that utilizing sampling along with 20% refuges never increased returns by more than 1% over the standard strategy of planting 80% insecticidal maize every season. A similar result was obtained by Foster *et al*. (1986), who showed the most economical strategy for this pest is not to scout and treat continuous maize each season with a soil insecticide.

Alfalfa pests in the United States

Calculation of ETs for alfalfa (*Medicago sativa*) pests should consider the effects of both the pests and management on forage quality (Buntin and Pedigo, 1985; Bechinski and Hescock, 1990; Hutchins and Pedigo, 1998). Forage quality determines the value of the hay for livestock and the price of the hay if it is sold. Forage quality is significantly determined by the age of the alfalfa at each of the two to three harvests per year.

Onstad and Shoemaker (1984) demonstrated how sampling and thresholds could be used to manage *Hypera postica* infesting alfalfa in the United States. In this case, control tactics include harvesting method, cutting time and insecticide use for this perennial forage crop typically harvested three times per year in New York. Onstad and

Shoemaker (1984) not only accounted for the amount of harvested forage but also the quality of the forage. Both are related to the age of the crop at the time of harvest: the amount increases while the quality decreases with age. Because they also included the natural control of the pest by a parasitoid in their model, Onstad and Shoemaker (1984) were able to develop multidimensional thresholds based on sampling of both the pest and the parasitoid. However, they concluded that a robust strategy is to harvest as early as possible without the use of insecticides. This strategy provides benefits only 1% less than optimal strategies involving the use of sampling, economic thresholds and possible insecticide use. But Onstad and Shoemaker did not include the cost of sampling in their calculations, and these costs would likely exceed the difference of a few dollars between strategies.

Onstad *et al.* (1984) used a mathematical model to develop EILs for the leafhopper, *Empoasca fabae*, on alfalfa. When there is more than one control tactic available at any given time, they discovered that one control tactic may be optimal for a low density (the first ET) while another, often more expensive, tactic may be better at a higher pest density (the second ET) sampled at the same time. Thus, for a given pest life stage at a given growth stage of the crop, harvesting the alfalfa (timing and type), treating the crop with insecticide (timing and type) and various combinations of these tactics may be the best control tactic that changes as sampled pest density changes. In essence, as the pest density increases in a crop growth stage, more expensive tactics may be necessary and therefore be assigned an EIL and ET (Onstad *et al.*, 1984).

Soybean pests in Brazil and the United States

ETs in soybean were first determined in the 1970s for the most important pests in both temperate and tropical areas. For the majority of soybean pests, it is now possible to use control measures based on scientific data, which contributes to appropriate insecticide use. However, for several recent soybean pests, such as mites, whiteflies and even some pod-feeding caterpillars, ETs have not yet been established (Bueno *et al.*, 2012). Nevertheless, soybean IPM can successfully be employed using current ETs.

ETs for defoliators feeding on soybean can differ slightly in different countries. In the USA, the ET is 35% defoliation for soybean at the vegetative stage and 20% for soybean at the reproductive stage (Andrews *et al.*, 2009). In Brazil, pest control measures are prompted by 30% defoliation (in the vegetative stage) or 15% defoliation (in the reproductive state) (Batistela *et al.*, 2012). Those small differences in ETs may be due to the differences in weather conditions of temperate (USA) and tropical (Brazil) areas, as well as different soybean cultivars (genetic backgrounds), which directly impact both plant and pest development.

Likewise, the recommended ETs for stink bugs differ slightly between the two countries. In the USA, the ET for seed-sucker stink bugs is three bugs (>0.6 cm) per row metre (Andrews *et al.*, 2009). In Brazil, the ETs vary depending on the production system (soybean for grain or seed production). For grain production, the ET is two bugs (>0.5 cm) per row metre. For seed production, the ET is only one bug (>0.5 cm) per row metre (Bueno *et al.*, 2015). Similar to the case for defoliators, ETs for stink bugs might differ between USA and Brazil due to different soybean cultivars and weather conditions. Moreover, different sampling strategies might yield different precision, which also plays an important role in ET establishment.

In spite of well-established ETs for most important soybean pests, soybean growers (both in Brazil and in the USA) hardly ever fully adopt those recommendations, for reasons that need to be further examined. Fearing a certain degree of yield loss, growers question the viability of recommended soybean ETs. Their most important doubts concern the early soybean cultivars with indeterminate growth habits. Plants with a lower leaf foliar index may be less tolerant to defoliation and produce pods for a longer period, which could also trigger higher stink bug outbreaks because pods are available longer.

In this respect, critics of the recommended ETs/EILs for soybean pests argue that thresholds were developed a long time ago (in the 1970s), while soybean cultivars and their production systems have since undergone dramatic changes. These include the already mentioned different cultivars, with improved yields and different growth habits (determinate and indeterminate). Soybean plants today usually have shorter maturity periods, among other traits improved by plant breeding programmes (Batistela *et al.*, 2012).

For example, during the 1970s, the Brazilian soybean average yield was 1500 kg/ha, while the current average yield is higher than 3000 kg/ha (Conab, 2017). Soybean production in the USA has evolved in a similar way. Increased plant production led growers to believe that a standardized amount of injury (such as the same percentage of defoliation) can cause a higher percentage of yield reduction, requiring a lower ET – an evaluation that is not justified. As discussed above, plant response to injury is not linear (Fig. 7.4) but includes tolerance and sometimes overcompensation, and thus the relationship between the intensity of injury and yield loss is also not linear (Fig. 7.4) (Peterson and Higley, 2001; Pedigo and Rice, 2009).

Another concern regarding ET accuracy in soybean IPM is related to how the EIL is calculated and how this calculation affects the ET. Considering that insecticides have generally become less expensive and soybean yields higher and more valuable, the EIL, and consequently the ET, should be lowered to reflect these changes. However, the EIL calculation considers the linear part of the curve that represents the relationship between insect injury and yield loss. If the ET is set much lower than the pest density at the EIL, there is a risk of establishing a pest level that falls into the tolerance or overcompensation part of the curve (Peterson and Higley, 2001). These circumstances must be considered before lowering the ET.

Earlier results reported soybean defoliation levels of up to 50% (Pickle and Caviness, 1984) or even 100% at the R2 stage (Gazzoni and Moscardi, 1998) without yield reduction. These results are best explained by the tendency of soybean to produce an excessive leaf area. This characteristic, also known from other plant species, allows plants to intercept maximum solar radiation for photosynthesis, even after a certain degree of defoliation (Brougham, 1956, 1958; Davidson and Donald, 1958; Watson, 1958; Murata, 1961; Stern and Donald, 1962). A small loss in the leaf area is compensated by greater light penetration to the lower leaves, which are normally shaded, resulting in an increased total output of photosynthesized plant products and, consequently, in a grain yield similar to non-defoliated plants or even slightly higher (Fig. 7.4) (Turnipseed, 1972).

Many of these studies were carried out in the 1970s or 1980s, but these levels (ETs) were confirmed in the more recent literature (Costa *et al.*, 2003; Reichert and Costa, 2003; Batistela *et al.*, 2012). Batistela *et al.* (2012) showed that even the newer soybean cultivars, regardless of their growth habit (determinate or indeterminate), can tolerate defoliation levels supported by the ET (30% in the

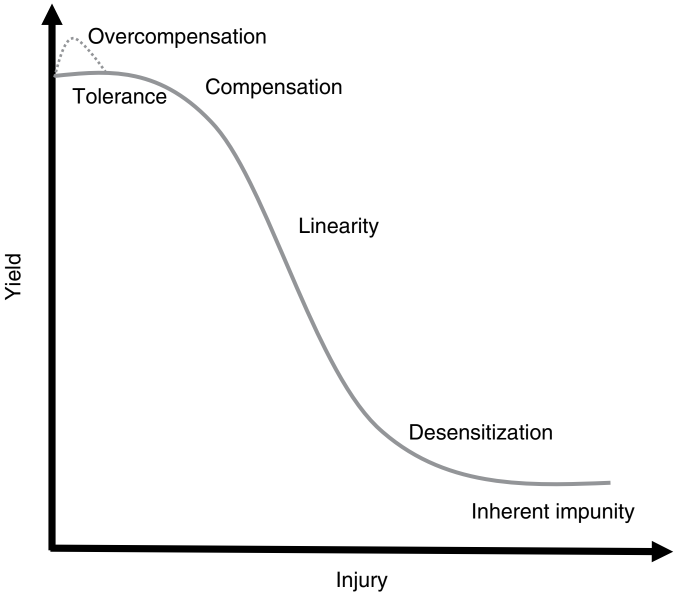

Fig. 7.4. Relationship between yield and injury triggered by pests. (Adapted from 'The damage curve – the relationship between yield and injury' from *Economic Thresholds for Integrated Pest Management* edited by Leon G. Higley and Larry P. Pedigo by permission of the University of Nebraska Press. Copyright 1996 by the University of Nebraska Press.)

vegetative state or 15% in the plant reproductive stage) without significant yield reduction.

Similarly, historic stink bug ETs can be safely adopted. Soybean plants tolerate two stink bugs (>0.5 cm) per row metre without any yield reduction or quality loss in response to pest feeding. When the current stink bug ET (two stink bugs ≥0.5 cm/m) was compared with a reduced ET (¼ ET = 0.5 stink bugs ≥0.5 cm/m) in a soybean cultivar of indeterminate growth habit, results indicated that a smaller population of stink bugs (0.50 stink bugs ≥0.5 cm/m) led to a similar yield (Table 7.1). In contrast, a smaller number of stink bugs required a total of six insecticide applications (and therefore higher economic and environmental costs) while the treatment under the recommended ET (two stink bugs ≥0.5 cm/m) required only two insecticide applications (Fig. 7.5). Given these results, an ET for stink bugs can be recommended in addition to the one for defoliators on soybean.

Critics of stink bug ETs have also stated that besides yield reduction, a decrease in soybean seed quality is caused by stink bug populations at the present ET recommendation. However, stink bug damage, evaluated by a tetrazolium test, was not significantly different between plots with an ET of 0.5 bugs/m and plots with an ET of 2 bugs/m (Table 7.1). In the control plots, dead embryos were found in 13.7% grains (Table 7.1), but the population density was more than 6 stink bugs/m from R5 to maturation (Fig. 7.5). A seed damage rate of 6% is legally accepted for certified seed production. Therefore, with respect to both yield and seed quality, there is no support for reducing the ETs currently recommended for stink bugs.

The results discussed here for both stink bug occurrence and defoliation refute the hypotheses that a standardized amount of injury (e.g. the same percentage of defoliation or stink bug feeding) is able to trigger a higher (or more valuable) yield reduction today than in the past. Instead, the results indicate that both defoliation and stink bug ET appear to lie within the tolerance phase of the damage curve (Fig. 7.4) and therefore no reduction is necessary for either of the ET values.

Positive results of using ETs without any risk to soybean yield are a prerequisite for a large-scale

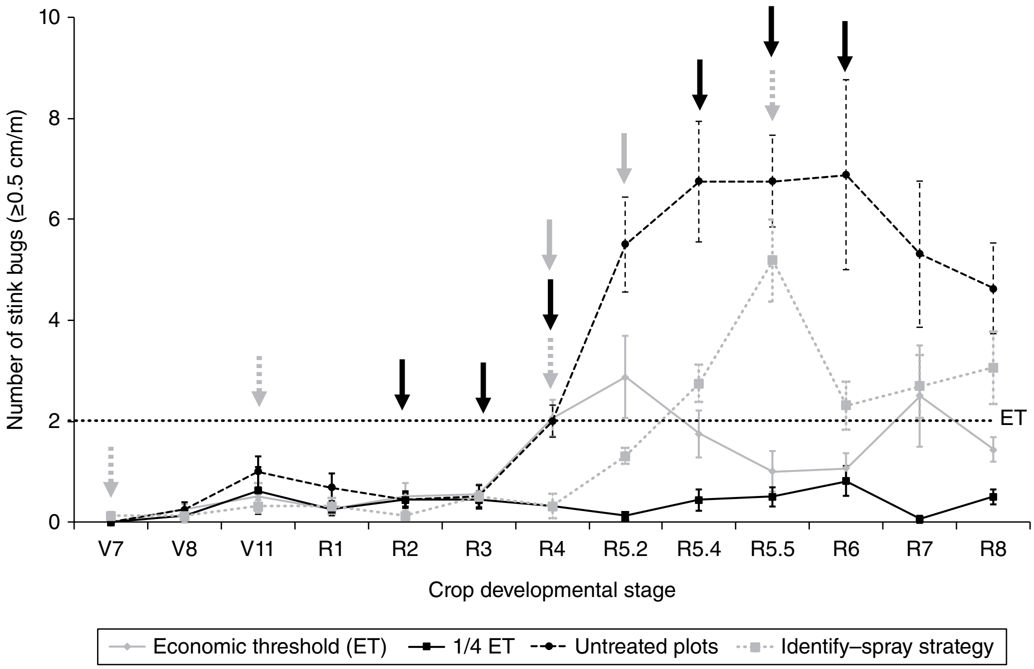

Fig. 7.5. Mean population (±SE) of stink bugs along the soybean crop developmental stages after different treatments (indicated by the arrows) for pest control. Municipality of Arapongas, State of Paraná, South Brazil, 2010/11 crop season. (Adapted from Bueno *et al.*, 2013.)

Table 7.1. Productivity and quality of the soybean seeds after the adoption of different management practices for the control of stink bugs. Municipality of Arapongas, State of Paraná, South Brazil, 2010/11 crop season. (Adapted from Bueno *et al*., 2015.)

Treatment	Number of insecticide sprays	Production (kg/ha)	Tetrazolium test (%)[2] Stink bugs damages (scale 6 to 8)
Economic threshold (ET) for stink bugs	2	3812.5 ± 96.5 a[1]	4.5 ± 2.6 b[1]
¼ of the ET for stink bugs	6	3992.9 ± 116.5 a	1.0 ± 0.4 b
Identify–spray strategy (grower control)	4	3678.9 ± 76.6 a	4.8 ± 2.3 b
Untreated plots	0	3267.2 ± 39.9 b	13.7 ± 2.2 a
CV (%)	–	4.78	30.00

[1]Means followed by the same letter in the column are not statistically different between each other by the Tukey test ($p > 0.05$);
[2]Original results transformed by $\sqrt{X}$.

Table 7.2. Mean productivity (±SE) of the soybean crop (kg/ha) obtained in experiments carried out under different pest management systems, at five different municipalities of two soybean producing Brazilian states (Goiás (GO) and Paraná (PR)), in the 2008/09 and 2009/10 crop seasons. (Adapted from Bueno *et al*., 2011a.)

		Pest management system		
Year	Location of the trials in Brazil (city, state)	IPM	Identify–spray strategy	Untreated plots
2008/09	Castelândia, Goiás	3180.4 ± 185.4 a	2981.5 ± 179.0 a	2555.1 ± 73.1 b
	Santa Helena de Goiás, Goiás	2447.0 ± 178.6^{ns}	2441.3 ± 208.2	2228.6 ± 166.5
	Senador Canedo, Goiás	2913.6 ± 200.4^{ns}	2832.9 ± 277.7	2487.3 ± 71.7
2009/10	Morrinhos, Goiás	4179.3 ± 128.6^{ns}	3902.5 ± 84.2	3797.5 ± 96.8
	Arapongas, Paraná	2992.6 ± 65.9 a	3175.7 ± 51.5 a	2667.8 ± 89.4 b

Means followed by the same letter in each line are not statistically different to each other according to the Tukey test ($p > 0.05$).
^{ns}Anova non-significant.

adoption of this strategy, as well as for larger soybean IPM programmes. Bueno *et al.* (2011a) observed no differences between recommended IPM and grower management plots (Table 7.2). It cannot be emphasized enough that an extended use of insecticides, apart from not providing better control and producing higher costs, can be harmful to humans and the environment, may aggravate pest resurgence, cause secondary pest outbreaks and increase pest resistance to primary insecticides (Meissle *et al.*, 2010; Tang *et al.*, 2010).

The benefits of adopting ETs in soybean IPM are remarkable according to the results of the programme carried out by the state of Paraná, Brazil, where state agronomists provide consultation for IPM to hundreds of growers. The programme has been running since the 2013/14 crop season, and the growers involved in the project have accepted the rational use of insecticides. The important results of this programme (Table 7.3) illustrate the benefits of adopting ETs and IPM in soybean cultivation. In spite of such convincing results, the adoption of soybean IPM is still not increasing enough. This is most likely due to the growers' focus on short-term benefits of pesticide use, which continues to obscure their understanding that sustainable pest management is urgently needed.

Conclusions

Economic thresholds are often used exclusively in combination with synthetic chemical insecticide treatments. However, we want to emphasize that a decision based on measuring a pest density or any other indicator can be used to control pests with different tools such as microbial insecticides, augmentative control with parasitoids or predators, or any other chemical or physical factor that can be deployed soon

Table 7.3. IPM results (mean) from soybean in Brazil. Programme carried out since 2013 in Paraná State, South Brazil. (Adapted from Conte *et al*., 2014, 2015, 2016, 2017, 2018.)

Variables/comparison		Crop season 2013/14	 2014/15	 2015/16	 2016/17	 2017/18
Number of insecticide sprays over the crop season	IPM	2.3 (46 growers)	2.1 (106 growers)	2.1 (123 growers)	2.0 (141 growers)	1.5 (196 growers)
	Average of Paraná State	5.0 (333 growers)	4.7 (330 growers)	3.8 (314 growers)	3.7 (390 growers)	3.4 (615 growers)
Days until first insecticide spray	IPM	60 days	66 days	66.8 days	70.8 days	78.7 days
	Average of Paraná State	33 days	34 days	36 days	40.5 days	43.6 days
Pesticide costs (bushels/ha)	IPM	5.31	4.41	4.41	5.07	3.13
	Average of Paraná State	11.09	11.02	8.82	9.04	7.27
Yield (bushels/ha)	IPM	108.53	132.72	125.89	142.20	137.11
	Average of Paraná State	107.30	129.19	120.59	141.53	134.44

after sampling is performed. Thus, economic thresholds as part of a control tactic, should not be associated only with chemical insecticides or any other product.

A control tactic is not a product, such as a chemical insecticide. It is not an ET. And few would consider sampling to be a tactic. Within the context of this chapter, a control tactic is the combination of all these. Thus, when we consider insecticide use in IPM, we mean that we have technology such as a chemical, we have a criterion for its use (the ET) and we have an appropriate sampling plan that permits decision making at the time chosen for management. It is very easy to only focus on one of these three components in research or extension. All three require dedication, hard work and funding, either within industry or in the public sector.

We have three recommendations. First, make sampling plans inexpensive, efficient and practical. Farmers need plans that can be adopted for everyday decision making, instead of satisfying scientific curiosity. Second, find new ways to integrate insecticides with other tactics in IPM. Well-designed cropping systems that include host-plant resistance, crop rotations and other factors described in Chapter 1 may still need insecticidal control of pests in seasons with high pest pressure. Note though that changes in design will likely require adjustments to older economic thresholds and possibly the associated sampling plan. Third, determination of EILs and ETs should be considered high-quality, cutting-edge science. Anyone who believes that they are not worthy of funding or promotion is mistaken. Society needs more new thresholds and more effort at revising and improving old thresholds.

Soybean pest management in Brazil provides an example of how the adoption of ETs and IPM can help reduce the reliance on pesticides in agriculture. Prior to the adoption of soybean IPM at the beginning of the 1970s, when insecticides were applied on a calendar basis, an average of six broad-spectrum insecticide applications were made per crop season. Following widespread adoption of soybean IPM, insecticides were used more appropriately by some growers who were in this programme. As a result, the use of insecticides was reduced to approximately two applications per crop season (Batistela *et al*., 2012). At present, IPM including the use of economics, sampling and long-term analysis has unfortunately not been used in the way that it should be by the majority of growers, causing the number of insecticide applications to increase. Soybean IPM in Brazil still has static ETs. As a consequence, the ‘identify and spray strategy’ approach already considered as inappropriate in the 1950s, is unfortunately still used in modern agriculture.

However, some economic analyses show that prophylactic (insurance) treatments with insecticides can be superior to IPM. Szmedra *et al.* (1990) concluded this for pest management for soybean production in the southern United States. They also believed that this is one reason why these farmers did not participate in IPM programmes. Reisig *et al.* (2012) evaluated management of *Oulema melanopus* that infests wheat in the southern United States. They found that fields under the prophylactic approach did not exceed a threshold as often as fields using IPM. Total cost of prophylactic management was also less per hectare, giving this approach an economic advantage over IPM. Reisig *et al.* (2012) concluded that adoption of IPM may depend on local conditions and more research is needed to reduce the cost of IPM in this system.

Ramsden *et al.* (2017) provided an important, realistic view of the status of economic thresholds for crop pests in the UK. They surveyed the cases for 34 major pests of field or arable crops. They concluded that most current economic thresholds for pests of arable crops in the UK are not based on published evidence and most are over 20 years old. For example, one of the 11 ETs based on a scientific publication has not been revised since 1961. Ramsden *et al.* (2017) also concluded that many of the sampling methods are impractical, do not guarantee sufficiently accurate estimates of pest density and are not described with sufficient detail to ensure consistency of pest assessment. However, this does not mean that ETs should be abandoned: more effort must be applied to study or update ETs for many pests on a variety of crops.

We do not focus on these limitations and complications to discourage readers. On the contrary, we are optimistic that ETs can remain useful even if they are not perfect. However, all stakeholders, including cooperative associations of growers and government policy makers, need to understand the difficulties, so that sufficient funds can be allocated on an annual basis to IPM research and extension services and related government agencies to develop new economic thresholds, revise old ETs and develop more efficient sampling plans (Leather and Atanasova, 2017; Ramsden *et al.*, 2017). Leather and Atanasova use the example of the 40-year old ET for *Sitobion avenae* on cereal crops in the UK to make this point clear. If an existing ET is based on a formula or model that has a few outdated parameter values, then only those parameters need to be measured again. Perhaps it as simple as adjusting the cost and price information.

Stakeholders should realize that the value of insecticidal pest control is dependent on more than the price of the chemical, the cost of its application and its efficacy in the field. The value is also dependent on our ability to evaluate when and where the chemicals should be used, which means understanding the pest population and the crop as much as we understand the insecticide. Without continual research and development, farmers will continue to return to either insurance applications of insecticides or treatments based on the calendar, not value.

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8

Economic Impacts of Integrated Pest Management Practices in Developing Countries

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The objective of this chapter is to summarize results of impact assessments of integrated pest management (IPM) in developing countries. The chapter focuses on assessments of agronomic and biological practices more than host-plant resistance and on insects more than other pests. To facilitate discussion of results of the IPM impact studies, it is organized around regions, recognizing that some types of IPM impacts and impact assessments may be more prevalent in one region than another. All of the studies cited have been subjected to peer review, although some to a lesser extent than others.

IPM is a crop protection strategy that integrates multiple practices, disciplines and concerns for economic, ecological and social wellbeing. Therefore, impact assessment of IPM can focus on a single IPM practice, a few practice(s) or on a complete IPM strategy. Assessing impacts of an IPM strategy is difficult because IPM adoption is usually only partial. Farmers and others who adopt IPM choose specific practices/components of an IPM strategy that suit their specific needs. They seldom select the whole menu or package of potential practices for the crop or other pest target.

Interest in IPM grew out of a desire to minimize the use of synthetic pesticides and their attendant risks, and to reduce physical and economic losses due to pests. Therefore, some IPM impact assessment studies focus on environmental benefits, although relatively few, and others on economic benefits. The philosophy of IPM is to manage pests by selecting practices that includes environmentally friendly options rather than trying to manage them with synthetic pesticides alone (Morse and Buhler, 1997). In developing countries, where poverty is a major concern, identifying who adopts IPM and who benefits economically or healthwise from that adoption can also be an important objective of IPM impact assessment.

Concerns over the growing use of toxic pesticides spurred the development of IPM programmes in developed countries (Morse and Buhler, 1997). Early IPM programmes emphasized scouting or monitoring pest populations and applying pesticides only when economic thresholds were crossed (Stern *et al*., 1959; Stern, 1973). Later, the programmes expanded to include other practices such as host-plant resistance, biological control with natural enemies and agronomic methods. Over time, the availability and application of these other IPM practices have grown. In fact, formal scouting of pests can be an important, but relatively small, component of IPM strategies in developing countries despite the high use of pesticides in many of them.

Effective IPM strategies provide (i) preventative means for managing the local environment to make

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it less favourable to pests, (ii) responsive practices that can be applied when pests exceed economically damaging thresholds and (iii) information pathways to impartial experts that farmers can access for pest diagnosis and potential IPM solutions when a major pest problem occurs. (For simplicity, we refer to farmers as the IPM clientele in this chapter, recognizing the many non-farm applications of IPM that also exist.) Preventative means include resistant crop varieties, crop rotation, intercropping and sanitation, among others. Responsive practices include bio-pesticides (microbial insecticides), augmentation with biological control agents and low toxicity synthetic pesticides. Information pathways may lead not only to expert diagnosis and advice, but to additional scientific research and on-farm testing. The results of that research and testing may eventually spread over a wide area.

Agricultural systems, farm size, research and extension systems differ by region and by country, and influence IPM programmes in developing countries. Pest management on small, semi-subsistence farms differs from that on high-input commercial farms. It also differs on staple crops compared with crops grown for export. IPM programmes on small subsistence farms have been influenced by external donor support, while IPM programmes on large commercial farms have been influenced more by demands of the market. For example, the Farmer Field School (FFS) IPM training approach supported by the United Nations Food and Agriculture Organization (FAO) has been aimed primarily at small producers and differs significantly from the commercially driven IPM approach aimed at farms attempting to export fruits and vegetables to the United States or Europe (Rejesus, Chapter 3). IPM programmes also evolve as economies grow and labour costs rise, forcing changes in agronomic practices such as weeding.

Some IPM programmes have been promoted by chemical companies (or entities such as CropLife, which is funded by those companies). Other programmes have been promoted by non-governmental organizations (NGOs) such as CARE or by national agricultural research and extension systems, such as the Kasakalikasan programme in the Philippines. Others have been promoted by international agricultural research centres such as the International Rice Research Institute (IRRI), International Centre of Insect Physiology and Ecology (ICIPE), and Centre for Agriculture and Bioscience International (CABI) (Plantwise). Others have been promoted by external donors such as FAO and the US Agency for International Development (USAID), which has supported the IPM CRSP (now IPM IL). Not surprisingly, IPM approaches suggested by these entities have differed, with the chemical company IPM model more supportive of pesticide use than are the other IPM models (Luther *et al.*, 2005, p. 182).

Pests continually evolve, which necessitates pest diagnostic and control capability that is independent of pesticide dealers, whose primary incentive is to sell chemicals. Alternative and impartial sources of pest diagnosis may be available from extension services, NGOs or private sector entities linked to the scientific community. Public agricultural research systems must continually generate new technologies and practices to manage evolving pests.

Some IPM impact assessments have focused on intensive IPM educational programmes such as FFS or extensive IPM educational programmes such as 'no spray for the first 40 days' and 'radio soap opera'. Others have evaluated adoption and impacts of IPM packages or practices developed through structured IPM research and spread through traditional extension methods. Others have evaluated IPM components such as classical and augmentative biological control. In this chapter, we cast a wide net to include all types of IPM evaluation studies, recognizing that some people might not consider partial IPM adoption 'true IPM'. However, few farmers, with the exception of high-management organic growers, adopt a complete set of IPM practices, yet many receive benefits from partial adoption, which can be large and counted. (As opposed to low-management organic growers who do not apply pesticides or other IPM practices and absorb crop losses.) Impact assessment can focus at the field, farm or market level. It can assess benefits to producers and/or consumers, consider environmental, health or nutritional benefits, identify poverty impacts and assess impacts by gender. We include impacts of various types in this chapter, with emphasis on aggregate impacts.

Results of IPM impact studies are summarized below in a set of regional tables, with no attempt to adjust the numbers presented for differences in time period or assessment method. Issues such as the choice of discount rate applied when valuing benefits and costs over time, care in addressing selection bias when evaluating effects of IPM training, size differences in the programmes being evaluated and difficulty in assessing benefits not priced in the market (such as many health and environmental benefits) complicate cross-study comparisons of the results. Although relatively few IPM practices and programmes have been subjected to any impact assessment, the large estimated benefits for several of the IPM practices speaks to the aggregate value of IPM research and training.

Impacts of IPM Practices in Asia

The literature on economic assessment of IPM in Asia focuses heavily on rice, but also includes several vegetables, fruits and other crops such as cotton. Rice is a major staple crop with major pesticide use, and large quantities of synthetic pesticides are applied to vegetables as well. Cotton has received attention in impact assessment due to the magnitude of its insect pest problems, heavy use of pesticides and the adoption of the component technology transgenic insecticidal (Bt) cotton in China and India.

Rice

Several IPM programmes in Asia have focused on irrigated rice. The 'Green Revolution' that swept across Asia in the 1970s brought intensive pesticide use along with its high-yielding crop varieties. The result was a sharp reduction in the natural enemy complex in many areas followed by major outbreaks of pests, such as the brown planthopper, *Nilaparvata lugens* (Hemiptera: Delphacidae) (Kenmore *et al*., 1984). An early and enduring response to problems caused by pesticide overuse has been the development and spread of FFS, beginning in Indonesia and eventually spreading around the world (Luther *et al*., 2005; Gallagher *et al*., 2009). Due the nature of FFS programmes, which involve season-long, intensive and hence high-cost contact between trainers and farmers, the spread of IPM through FFS has been limited in terms of total farmers reached. Several economic impact assessments of FFS have been conducted, with their results summarized by Rejesus in Chapter 3 of this volume.

Beginning in the late 1980s, FFS were set up in Indonesia, the Philippines and elsewhere in Asia with support from FAO to teach farmers how to manage their white rice stem borer and brown planthopper pests by growing rice without insecticides and allowing beneficial insects to re-establish in rice fields and reduce their pest problems (Bentley, 2009). Each FFS reaches about 25 farmers, with meetings held each week during the growing season. Part of the rationale behind the FFS method is that participants, selected partly based on their linkages to other farmers, will teach their non-trained neighbours. Thus, spread of information to non-participating farmers is one determinant of FFS impact. Rice FFS were designed to augment existing IPM programmes that were based around pest-resistant rice varieties developed in the 1970s and 1980s. Despite those varieties, farmers were applying large quantities of pesticides, which were destroying beneficial insect populations. Several countries in Asia including Indonesia, the Philippines and India had been subsidizing pesticide use since the 1970s. For example, the Indonesian government was spending more than $100 million per year on pesticide subsidies. It began cutting back those subsidies in late 1980s, which significantly reduced their use and was complementary to the FFS IPM programme that encouraged farmers to reduce pesticide use (Gallagher *et al*., 2009). The reductions in pesticide use in the late 1980s and early 1990s in Indonesia, combined with the expansion of the FAO IPM programme in Asia and subsequent FAO Global IPM Facility, was a catalyst for growth in FFS-style IPM programmes in several countries.

FFS programmes (rice and other crops) have reached at least 1–5% of Asian farm households (Van Den Berg and Jiggins, 2007). The typical cost per participating farmer of $20–50 has constrained its spread to a larger set of farmers as donor and public extension systems funds are limited. Nevertheless, FFS have become a fixture in many IPM programmes in Asia (and other regions as noted below) and been the subject of several impact assessments. A large number of non-peer reviewed reports find significant localized impacts in FFS, while peer-reviewed journal impact assessments find limited support for widespread impacts beyond programme participants (Feder *et al*., 2004). Because participants in FFS programmes typically self-select into the programmes or are selected based on potential influence with their neighbours, impact assessments are often subject to selection bias. Evidence of sustained impacts on use of IPM practices, reductions in pesticide use over time or

IPM knowledge spillovers to neighbouring farmers is limited (Feder *et al*., 2004). FFS impacts are difficult to evaluate because FFS is partly a farmer education programme with potential impacts on agro-ecological knowledge that might pay off over time (Van Den Berg and Jiggins, 2007). In some cases, it appears that farmers who attended FFS programmes have influenced public policies (FAO, 1998; Resosudarmo, 2008), and policy impacts are difficult to assess. One study (Rejesus *et al*., 2009) that did control for selection bias, found a significant negative effect of FFS on insecticide use in three south Vietnam provinces. A study by Rola *et al*. (2002) in the Philippines found that FFS participants may not spread what they learn to their neighbours but they tend to retain what they learn.

The sustained widespread prevalence of FFS programmes, not just in Asia or for rice but for multiple crops around the world, indicates that many decision makers feel they are having an impact. But, it seems clear that FFS is not the optimal method for achieving fast and widespread application of IPM recommendations within a country (Harris *et al*., 2013). Other methods as such as demonstrations with field days and mass media campaigns can be more cost-effective in raising awareness and adoption of IPM practices, at least for rice. For example, the media broadcast of the simple message in Vietnam in 1994 to not apply insecticides for the first 40 days after sowing rice reached about 92% of the 2.3 million farm households in the Mekong Delta (Huan *et al*., 1999). This no-spray message, combined with the implementation of FFS programmes that reached 4.3% of the farm households in the Delta, caused farmers to reduce their insecticide sprays per season by 70%. Most of the insecticide reduction was due to the no-spray message, because it reached many more farmers than FFS. But those farmers who received the no-spray message and attended FFS reduced their sprays by 83% so the two types of IPM approaches are certainly complementary (Huan *et al*., 1999). Unfortunately, a study a few years later (Rejesus *et al*., 2009) detected no significant effect of the no-spray message on insecticide use, so repeated education is essential.

Other types of mass media approaches have also been tested and found successful for rice IPM in Asia. For example, radio spots and dramas with IPM content were broadcast in the Philippines in the 1980s (Pfuhl, 1988). Entertainment education for IPM adoption was tested in Vietnam in 2004 with a radio soap opera that was launched and ran for 104 episodes (Heong *et al*., 2008). An experiment was set up in which an audience of farmers in one district received the broadcast and farmers in another did not. Insecticide sprays were reduced by 60% for those who received the broadcast. Pre- and post-broadcast surveys were run and farmers in the district that received the broadcast reduced their sprays by 30%. Farmer beliefs and attitudes about insects and health effects of pesticides were also changed (Heong *et al*., 2008).

There are approximately 200 million rice farmers in Asia alone and the challenge for IPM programmes is to reach the farmers cost-effectively as most extension programmes have tight budgets (Escalada and Heong, 2004). And in some areas, extension personnel are non-existent. Mass media approaches would seem to be an essential component of a publicly supported rice IPM programme that hopes to achieve widespread results, at least for IPM practices not embedded in products such as pest-resistant crop varieties, pheromones traps or bio-pesticides. For the latter, the private sector may have an incentive to market and sell them. However, as the study by Rejesus *et al*. (2009) indicates, messaging may not have much staying power and needs repeating periodically to remain effective.

Rodents are more damaging to rice than they are to most other crops. Pre-harvest rice losses in Asia are estimated to be between 5 and 10% (Singleton *et al*., 2005). Some progress has been made in reducing rodent populations in rice fields through community coordination to increase hygiene around fields and villages, adjusting planting dates to disrupt the rodent biological cycle by affecting their food supply at crucial times and reducing chemical use to encourage natural predators such as birds of prey. A study in Indonesia demonstrated that the economic benefits of such integrated rodent management is equal to or greater than conventional management based on synthetic rodenticides (Singleton *et al*., 2005). Unfortunately, IPM solutions to rodent problems have not been adopted on a large scale.

Vegetables and fruits

IPM programmes in vegetables and fruits have been common in Asia since the mid-1990s, initiated in part over concerns about the heavy use of pesticides on high-value crops with many pest problems. Demand also has grown for vegetables and fruits as incomes have risen in the region. The expansion of FFS programmes in rice, financed in part by UN agencies FAO and IFAD and by several NGOs, may also have contributed to some national agricultural research institutions extending their IPM programmes to vegetables.

The World Vegetable Center and USAID-funded programmes, such as the IPM CRSP, were early and sustained supporters of vegetable IPM research in Asia. Much of the early research focused on individual IPM practices for prioritized pests and vegetables in countries such as the Philippines, Bangladesh, India and Indonesia. For example, practices were developed and tested to graft tomatoes and eggplant to reduce losses to bacterial wilt, introduce pheromone traps to manage fruit flies in cucurbits and squash, multiply and apply local bio-pesticides (e.g. *Bacillus thuringiensis*, Bt, or nucleopolyhedrosis viruses) to reduce caterpillar damage in crucifers, produce compost inoculated with *Trichoderma* to reduce soil disease problems, and improve timing of hand weeding and herbicide use in onions among others (Miller *et al*., 2005; Norton *et al*., 2005; Rakshit *et al*., 2011). These practices were integrated into IPM packages that were tested and demonstrated in farmers' fields (Norton *et al*., 2016).

IPM packages are now common for several fruits and vegetables in some countries, although farmers continue to be selective in which practices they adopt. The most commonly adopted practices are those that involve products sold by the private sector such as pest-resistant crop varieties, pheromone traps and bio-pesticides as well as simple practices such as removing infected plants and improving the timing for hand weeding (Ricker-Gilbert *et al*., 2008). For a small set of pests, such as the papaya mealybug, *Paracoccus marginatus* (Hemiptera: Pseudococcidae), classical biocontrol has been extraordinarily beneficial because once the beneficial insects were multiplied and released, they were highly effective in reducing crop losses, and they spread on their own without the farmers having to do anything (Myrick *et al*., 2014). Myrick *et al.* estimate economic benefits in excess of $500 million in southern India (Table 8.1).

Most, but not all, vegetable IPM impact assessments focus on individual practices for specific crop/pest combinations. For example, Francisco and Norton (2002) find an impact of $23 million in net present value over 15 years for a bio-pesticide programme (for cutworms) and weed management control (for purple nut sedge) on onions in a relatively small area (San Jose and Bongabon in Nueva Ecija) of the Philippines. Cuyno *et al.* (2001) assess the economic value of environmental and health benefits of an onion IPM programme in the Philippines and estimate a total annual benefit of $150,000 per year in six villages.

Estimating the value of health and environmental benefits of IPM is a challenge given the diversity of difficult-to-measure effects and the fact that most of those effects are not priced in the market (Norton and Swinton, 2008, 2010). Cuyno *et al.* (2001) use contingent valuation to assess the value of reduced health and environmental risks due to IPM-induced pesticide reductions. Many others (e.g. Sharma *et al*., 2015; Sharma and Peshin, 2016) use the Environmental Impact Quotient formula from a study by Kovach *et al.* (1992) in their assessments, simply due to ease of use. Unfortunately, the Environmental Impact Quotient employs weights on risks of pesticides to environmental categories that are arbitrary with the result that applying them gives meaningless results. Choice experiments, synthetic auctions or other recent methods developed by natural resource economists would be preferable (Champ *et al*., 2017).

Perhaps due to the difficulty of valuing environmental benefits, several studies simply assess impacts of IPM on pesticide use as a proxy for environmental benefits. Sanglestsawai *et al.* (2015) and Yorobe *et al.* (2011) find insecticide-reducing effects of FFS training on onions in the Philippines, while Gautam *et al.* (2017) find that IPM training significantly reduces pesticide use on aubergine in four districts in Bangladesh. Rahman *et al.* (2018) find an average of $25 in pesticide savings per IPM adopter on six vegetables in Bangladesh. Each of these studies uses specific techniques to control for the problem of selection bias that was mentioned above. Results of these and other economic and environmental assessments of IPM in Asia are listed in Table 8.1.

Other crops

It appears that the largest non-rice and non-vegetable IPM programme in Asia has been in cotton, due in part to efforts by FAO in a set of FFS projects in China, India, Pakistan, Bangladesh and Vietnam (Ooi *et al*., 2005) and to integration of Bt cotton into the IPM programmes of China and India. Data are drawn from relatively small sample sizes, but with some effort to control for selection bias, a set

Table 8.1. Summary sample of IPM impact assessment results for crops in Asia.

Country, author(s), date	Crop	IPM practice(s)	Net economic benefits to producers and consumers (millions)	Other benefits (poverty, nutrition, environment, per unit returns)
Philippines; Mutoc, 2003	Aubergine	Grafting		Projected increase of 0.09–0.6 kcal/person/day in Nueva Ecija
Philippines; Francisco and Norton, 2002	Onions	NPV and cultural	$23.5 over 15 years in two regions	
Philippines; Miller *et al*., 2005	Aubergine	Cultural		$2500/ha to producers
Philippines; Cuyno *et al*., 2001	Onions	Cultural		$150,000 in environmental benefits to six villages
Philippines; Sanglestsawai *et al*., 2015	Onions	FFS IPM diffusion		Significant reduction in pesticide use
Philippines; Yorobe *et al*., 2011	Onions	FFS IPM diffusion		Significant reduction in pesticide use
Bangladesh; Debass, 2001	Aubergine, cabbage	Cultural practices	$26–29 over 30 years in two regions	
Bangladesh; Rakshit *et al*., 2011	Sweet gourd	Pheromone traps	$3–6 over 15 years in four districts	
Bangladesh; Guatam *et al*., 2017	Aubergine, bitter gourd	IPM training		Significant reduction in pesticide use and higher gross margin per hectare
Bangladesh; Rahman *et al*., 2018	Aubergine, tomato, bitter gourd, cabbage, cucumber and country bean	IPM research and training	$0.768 per year in four districts	$25 per IPM adopter and reduction in pesticide use
China, India, Bangladesh, Pakistan and Vietnam; Ooi *et al*., 2005	Cotton	IPM training		Average benefits of $190 per household trained, with wide variation by country
India; Natajaran, 2013	Onions	Cultural		$750/ha to producers; $124/ha in pesticide cost savings
India; Myrick *et al*., 2014	Papaya, tomato, aubergine, others	Biocontrol	$524–1340 over 5 years	

of seven commissioned impact assessment studies found that gross margins for cotton farmers trained in IPM were higher in six out of seven countries and ranged from –$37/ha in Bangladesh to almost $500/ha in Hubei province, China. Average health benefits averaged $21 per FFS graduate and pesticide costs were reduced from 0 to $88/ha, depending on the country.

The introduction of Bt cotton has had a major impact on reducing insecticide sprays on cotton in China and India (Kathage and Qaim, 2012). Unless incorporated into a broader IPM programme, some people might not consider the technology to be part of IPM. Unless embedded in an IPM programme, Bt cotton could result in the same resistance problems as have plagued pesticides. However, there is no denying the large positive economic and environmental benefits of introducing this pest management component into the cotton IPM programmes in China and India. The relative lack of pest resistance to Bt cotton indicates another IPM tactic (refuge area) may be present as well. Using panel data from 2002 to 2008, Kathage and Qaim (2012) found that Bt cotton increased cotton yield by 24% in India and raised living standards for cotton growers by 18%, a major increase for a single pest management component. Impacts on pesticide use have been equally significant. They estimate that Bt cotton farmers spray 30 kg/ha (78%) less pesticides than non-Bt cotton farmers (and most farmers are now Bt cotton farmers in both India and China).

Impacts of IPM Practices in Africa

IPM programmes in Africa lag behind those in Asia, but have experienced significant successes. As reported by Kiss and Meerman (1991), several IPM efforts were undertaken years ago on millet in Mali; cotton in Zimbabwe, Togo and Sudan; coffee in Kenya; rice in Burkina Faso and Madagascar; mango in Togo, and Africa-wide with the biological control of cassava mealybug *Phenacoccus manihoti* (Homoptera: Pseudococcidae). The development of mosaic disease-resistant Tropical Manioc Selection varieties in Tanzania in the 1970s by the International Institute for Tropical Agriculture (IITA) increased cassava yields by 40% nationwide (Nweke, 2009). Subsequent research and diffusion programmes for TMS-resistant cassava material in Nigeria, Ghana and Uganda obtained similar results (Nweke, 2009).

Except for the biocontrol programme for cassava mealybug, relatively few of the early IPM efforts were subjected to economic impact assessments, unless those assessments were part of an overall assessment of returns to agricultural research (Maredia *et al.*, 2001). The cassava mealybug programme was a major success and evaluated by Norgaard (1988) and Zeddies *et al.* (2001). In recent years, more IPM programmes have been subjected to impact assessments (Moyo *et al.*, 2007; Rusike *et al.*, 2010; Waddington and White, 2014; Kibira *et al.*, 2015; Owusu and Kakraba, 2015; Muriithi *et al.*, 2016; Kassie *et al.*, 2018 among others).

The cassava mealybug programme introduced the biological control agent *Anagyrus (Epidinocarsis) lopezi* (Hymenoptera: Encyrtidae) into sub-Saharan Africa by IITA from South America where cassava mealybug is native. Costs and benefits for the biological control were calculated over 40 years (1974–2013) for 27 African countries (Zeddies *et al.*, 2001). It is estimated to have saved $26/ha and a total programme cost of $47 million resulted in $9 billion in benefits, and a benefit–cost ratio of about 200:1 and even higher under alternative price scenarios (Zeddies *et al.*, 2001). Norgaard (1988) estimated a benefit–cost ratio of 149:1 based on realized and projected benefits and costs for 1977–2003.

Recent evaluations of other IPM programmes in Africa have indicated more modest impacts compared with the cassava mealybug programme. Kassie *et al.* (2018) examined the farm and aggregate-level economic benefits of the 'push–pull' farming (PPF) system in Kenya. Push–pull protects maize, millet and sorghum from two pests, stem borer and *Striga*, a parasitic weed. The PPF system intercrops cereals with the fodder legume *Desmodium* to repel (push) stem borers by emitting volatile chemicals. *Desmodium* also secretes chemicals from its roots and suppresses *Striga* by causing early germination of *Striga* seeds before they can attach to cereal roots. The cereal crops are surrounded by a border (or trap crop) such as *Pennisetum purpureum* (Napier grass) or *Brachiaria* species that attract (pulls) stem borers away from cereal plants. They estimated a 61.9% increase in maize yield, a 15.3% increase in cost and a 38.6% increase in net profits per acre for adopters. The 14.4% level of adoption in western Kenya resulted in $72 million in net benefits and reduced number of people below the poverty line by about 75,000.

Another evaluation of IPM in Kenya (Meru County) examined the effects of five IPM practices on suppression of fruit flies in mango (Muriithi *et al.*, 2016). They estimated savings in yield losses, reductions in pesticide expenditures and increased profits from (i) spot-spraying of food bait, (ii) male annihilation through mass trapping, (iii) application of the bio-pesticide *Metarhizium anisopliae*, (iv) releases of the parasitoids *Fopius arisanus* and *Diachasmimorpha longicaudata*, and (v) use of orchard sanitation. For IPM adopters, they reported an average reduction of 17% in yield losses, a 45% reduction in pesticide expenditures and a 48% increase in net income (without considering family labour cost). An earlier study by Kibira *et al.* (2015) of a similar IPM package, but without the bio-pesticide, for the same crop, pest and location found that mango rejections for export were reduced by 54.5%, pesticides costs were 46.3% lower and net income per acre rose by 22.4% for IPM adopters.

Biological control programmes have received substantial evaluation in Africa. For example, Midingoyi *et al.* (2016) evaluated the long-term impact of an ICIPE-supported biological control programme for cereal stem borers in East and Southern Africa. The research focused on Kenya, Mozambique and Zambia where four biological control agents – the larval parasitoids *Cotesia flavipes* and *Cotesia sesamiae*, the egg parasitoid *Telenomus isis* and the pupal parasitoid *Xanthopimpla stemmator* – were released to control stem borers of maize and sorghum. They estimated the net present value over 20 years to reach $272 million for both crops, with a high of $142 million for Kenya. Biological control helped to lift 57,400 people per year out of poverty in Kenya, 44,120 in Mozambique and 36,170 in Zambia.

Bokonon-Ganta *et al.* (2002) assessed the socio-economic impact of releasing natural enemies to manage mango mealybug in Benin. They found that releasing the bio-agents increased a mango producer's income by $328 on average per year and a net annual economic benefit for the country of $50 million. The present value of these benefits over 20 years was calculated to be $531 million as compared with a present value of the programme cost of $3.66 million. Macharia *et al.* (2005) assessed the potential economic impact of controlling diamondback moth (*Plutella xylostella*) on cabbage with an exotic parasitoid in Kenya. They estimated a net present value of $28.3 million nationwide over 25 years and a benefit–cost ratio of 24:1 with an internal rate of return of 86%.

De Groote *et al.* (2003) estimated the benefits of biological control of water hyacinth in southern Benin. They found total economic benefits per year of $30.5 million, and $260 million in discounted benefits over 20 years.

Rusike *et al.* (2010) estimated impacts on yields and caloric intake of a set of 'research for development' interventions for cassava in Malawi. Among those interventions were large-scale tissue culture and rapid multiplication of virus-free planting materials for farmers. They measured 23% higher yields for adopters of the practices and the months their households could meet their minimum caloric intake increased by two-thirds.

Waddington and White (2014) examined the results of FFS programmes in Africa, Asia and Latin America. They found FFS to be effective in raising impacts of direct programme participants by an average of 19%, but no convincing evidence of spillover benefits to neighbouring farmers. They concluded that FFS has had only small-scale impacts (Waddington and White, 2014, p. 21). Larsen and Lilleor (2014) examined effects on food security and poverty of FFS for a large 'basket' of improved farming technologies in northern Tanzania. They found strong effects on food security but not poverty. Davis *et al.* (2011) found positive effects on incomes of FFS participants in Uganda, Tanzania and Kenya, but did not specify the crops or IPM technologies included in their study.

Some authors have examined the distributional impacts of IPM programmes. For example, Moyo *et al.* (2007) focused on poverty-reducing impacts of virus-resistant groundnut varieties in eastern Uganda. They estimated annual benefits of $50–100 per household, total economic benefits of $34–62 million in eastern Uganda and a poverty rate drop of about 0.5–1.5%, depending on assumptions.

In non-published (but often based on theses) literature, Nouhoheflin *et al.* (2009), Debass (2001) and others have assessed economic and other impacts of IPM. For example, Nouhoheflin *et al.* (2009) evaluated the economic benefits of IPM aimed at managing a virus problem on tomatoes in Mali. They found that a host-free period reduced insecticide costs by more than $200 per hectare; economic benefits for Mali over 18 years were estimated at $21–24 million. Debass (2001) assessed the economic benefits of seed dressing to manage rodents and fungal infections on beans in Uganda. He estimated aggregate benefits of $202 million over 20 years. Coulibaly *et al.* (2004) estimated the economic benefits (net present value) of managing the cassava green mite with classical biological control to be $74 million in Benin, $383 million in Ghana and $1688 million in Nigeria over 17 years. A follow-up study in Ghana (Aidoo *et al.*, 2016) estimated lower but still sizable net economic benefits from biological control of cassava green mite to be $228.5 million over 40 years.

It is clear that classical (inoculative) biological control (Zeddies *et al.*, 2001; Coulibaly *et al.*, 2004; Muriithi *et al.*, 2016) has resulted in the largest economic impacts from IPM in Africa. Returns to augmentative biological control are smaller, due to the need for continual multiplication of beneficial insects, but they too may have a promising future (Guerci *et al.*, 2018). Other practices such as application of pest-resistant crop varieties and biopesticides are growing in importance and have the benefit of being embedded in products that the private sector has incentive to sell. Knowledge-intensive practices such as grafting, altering planting dates and host-free periods will likely continue to diffuse slowly and have less impact.

Table 8.2. Summary sample of IPM impact assessment results for crops in Africa.

Country, author(s), date	Crop/ resource	IPM practice(s)	Net economic benefits to producers and consumers (millions)	Other benefits (poverty, nutrition, environment, per unit returns)
Sub-Saharan Africa; Norgaard, 1988	Cassava	Biocontrol of cassava mealybug		Benefit–cost ratio of 149:1 over 25 years
Sub-Saharan Africa; Zeddies *et al*., 2001	Cassava	Biocontrol of cassava mealybug	$9 billion over 40 years in 27 countries	
Kenya; Kassie *et al*., 2018	Maize	Push–pull	$72 million	75,000 people brought above poverty line
Kenya; Muriithi *et al*., 2016	Mango	Five IPM practices		45% reduction in pesticide costs and 48% increase in income for 1122 farmers
Kenya, Mozambique and Zambia; Midingoyi *et al*., 2016	Maize and sorghum	Biological control of cereal stem borers	$272 million over 20 years	0.35%, 0.25% and 0.20% yearly reduction in poverty in three countries for a total of 137,690 people
Kenya; Kibira *et al*., 2015	Mango	Four IPM practices		43% reduction in pesticide costs and 22% increase in income per hectare
Malawi; Rusike, *et al*., 2010	Cassava	Virus-free planting material		23% higher yields
Uganda; Moyo *et al*., 2007	Groundnuts	Virus-resistant variety	$34–62 million over 15 years	0.5–1.5% reduction in poverty rate in the eastern region
Mali; Nouhoheflin *et al*., 2009	Tomato	Host-free period	$21–24 million over 18 years	$200 per hectare per year
Kenya; Macharia *et al*., 2005	Cabbage (*ex-ante*)	Biological control of diamondback moth	$28.3 million over 25-year period	
Uganda; Debass, 2001	Beans	Seed dressing	$202 million over 20 years in two districts	
Benin; Coulibaly *et al*., 2004	Cassava	Biological control of green mite	$74 million over 17 years	
Ghana; Coulibaly *et al*., 2004	Cassava	Biological control of green mite	$383 million over 17 years	
Nigeria; Coulibaly *et al*., 2004	Cassava	Biological control of green mite	$1,688 million over 17 years	
Benin; Bokonon-Ganta *et al*., 2002	Mango	Biological control of mango mealybug	$531 million over 20 years	
Ghana; Aidoo *et al*., 2016	Cassava	Biological control of green mite	$228.5 million over 40 years	
Benin; De Groote *et al*., 2003	Water	Biological control of water hyacinth	$30.5 million per year and $260 million over 20 years	

Impacts of IPM Practices in Latin America/Caribbean

IPM programmes in Latin America have expanded in recent years, although relatively few IPM economic impact assessments have been completed. Cotton, soybean and potato IPM programmes were introduced in Argentina; passion fruit and coffee IPM in Colombia; IPM for sugarcane, soybean, tomato and wheat in Brazil; tomato and crucifer IPM in Mexico; potato IPM in Peru and Ecuador; and vegetable IPM in Ecuador, Honduras and Guatemala (Barrera *et al*., 2002; Hoffmann-Campo *et al*., 2003; Godtland *et al*., 2004; Mauceri *et al*., 2007; Sparger *et al*., 2011; Carrion Yaguna, 2013, 2016a, 2016b; Colmenarez *et al*., 2016). FAO has supported FFS programmes in several of these countries. IPM impact assessments have focused largely on potatoes and vegetables, due in part to long-standing IPM projects supported by the International Potato Center (CIP) and by the IPM Collaborative Research Support Program (IPM CRSP) funded by the US Agency for International Development.

Godtland *et al*. (2004) apply propensity score matching to a set of survey data from potato growers in Peru and project a 32% potential increase in productivity for IPM adopters from an FFS IPM programme if knowledge gains do not dissipate over time. Their study was one of the first, along with Feder *et al*. (2004), to control for selection bias in economic assessments of IPM programmes. A series of IPM impact assessments were completed in Ecuador for potatoes and in Honduras for vegetables with support from the IPM CRSP (Table 8.3). Barrera *et al*. (2002) and Quishpe (2001) assessed impacts of the late blight-resistant potato variety, Fripapa, in Ecuador, and Barrera *et al*. (2004) of IPM in general in the Carchi region of Ecuador. Both studies found savings in pesticide costs of more than $200 per hectare for adopters. Fripapa generated more than $138,000 in net economic benefits, a relatively small number because it was not preferred in the market.

Table 8.3. Summary sample of IPM impact assessment results for crops in Latin America

Country, author(s), date	Crop	IPM practice(s)	Net economic benefits to producers and consumers (millions)	Other benefits (poverty, nutrition, environment, per unit returns)
Peru; Godtland *et al*., 2004	Potatoes	FFS – multiple		32% potential increase in productivity for adopters
Ecuador; Barrera *et al*., 2002	Potatoes	Resistant variety	$0.138	$209/ha in pesticide cost savings for adopters
Ecuador; Barrera *et al*., 2004	Potatoes	FFS – multiple		$314 in pesticide cost savings for 4600 adopters
Ecuador; Mauceri *et al*., 2007	Potatoes	Multiple		$270–560/ha for adopters
Ecuador; Carrion Yaguna, 2016a, 2016b	Potatoes	Multiple		$220/ha in pesticide cost savings for adopters
Ecuador; Baez, 2004	Plantain	Sanitary leaf pruning, weevil traps	$50–53 over 15 years	$8–9.5 million benefits accrue to labour
Honduras; Sparger, 2011	Aubergine, tomatoes, peppers, others	Grafting, solarization, cover crop, etc.	$17 over 15 years nationwide	$5 million to the poor
Honduras; Secor, 2012	Maize, onions, tomato, pepper	Multiple	$70 per year	Several improvements in gender indicators
Ecuador; Clements *et al*., 2016; Ochoa, 2016	Naranjilla	Multiple	$6.55	$3.67 million in deforestation avoided

FFS, Farmer Field School; IPM, integrated pest management.

Mauceri *et al.* (2007) and Carrion Yaguna *et al.* (2016a, 2016b) also evaluated impacts of IPM on potato in Ecuador. Mauceri *et al.* estimated $270–560 per hectare in benefits for adopters in Carchi Province, and Carrion Yaguna *et al.* (2016a, 2016b) estimated $220 per hectare in net benefits. The latter study surveyed the same area as Mauceri *et al.* (2007), 10 years after the IPM training had ended. IPM adoption had declined to some extent, but many farmers in the area were still using IPM, implying significant durability of the IPM messages. Baez *et al.* (2004) focused on plantain IPM in the coastal region of Ecuador and estimated $50–53 million in aggregate benefits.

Clements (2016) and Ochoa *et al.* (2016) examined impacts of an IPM programme on naranjilla, a crop grown in an environmentally sensitive area in Ecuador. They found more than $6.55 million (net present value) in direct benefits over 20 years and $3.67 million in environmental benefits due to deforestation avoided. The latter was due to carbon sequestration.

A study by Sparger *et al.* (2011) provided perhaps the most extensive economic assessment of an IPM programme in Latin America. They examined the impacts of five IPM practices (grafting, biological control, soil amendment and pressure regulating valve on sprayer) for four crops (tomato, aubergine, onion and peppers) in Honduras. Total economic benefits (net present value) over 15 years totalled $17 million. They disaggregated the benefits by crop, practice and income quantile, with approximately 74% of onion benefits, and 66% of pepper, 67% of tomato and 94% of aubergine benefits received by the bottom three income quintiles of the population and $5 million to the poor. Secor (2012) projected IPM benefits for several existing IPM technologies on four crops in Honduras, including a major grain crop, maize, and attempted to apportion benefits by gender. He found total benefits of approximately $70 million and several improvements in gender (female) indicators.

Summary and Discussion of Economic Impacts of IPM in Developing Countries

IPM is sometimes criticized, informally if not in journal articles, for being too complex or knowledge-intensive for farmers in developing countries. The implication drawn is that IPM is a low-return investment, or at least a lower-return investment than alternative technologies such as improved crop varieties. That characterization is misleading. It is true that IPM, by its very nature, attempts to combine a variety of methods to manage a pest complex for each crop. However, components of an IPM package have been shown to have payoffs for individual pests (Tables 8.1–8.3), and when IPM succeeds in reducing use of broad-spectrum pesticides, it has 'nature on its side' through expanding populations of beneficial organisms. As Ricker-Gilbert *et al.* (2008) note, simpler practices may be adopted faster than more complex ones, but that does not imply that partial adoption of IPM makes it a poor investment. IPM also generates health and environmental benefits that are no less real than yield changes, but are not as easily quantified.

In most cases, obtaining IPM impacts in developing countries requires conscious adoption of IPM practices by individual users. Several characteristics of IPM can reduce chances of adoption as compared with the users simply doing nothing or applying pesticides alone. First, low-income farmers in developing countries tend to (i) be risk-averse, (ii) value the present more than the future and (iii) place a lower value on environmental benefits (in economics terminology, have a lower income elasticity of demand for environmental benefits) than wealthier individuals (Norton *et al.*, 2015). They also may have less access to IPM education. Pesticide dealers are aware of these characteristics and provide pest diagnostics and pest recommendations that simplify pest management decision making, and may even provide credit when cash is low for input purchases. Synthetic pesticides also tend to kill pests more quickly than IPM practices such as bio-pesticides and may not require as much precision in their application. The fact that impact assessments of IPM often obtain high economic returns is a testament to their effectiveness at least in small geographic areas.

The high returns documented in this chapter for specific cases are also only a fraction of overall IPM benefits around the world. Most IPM programmes have not been subjected to evaluation, yet the returns estimated in the few – especially biocontrol – case studies presented above (>$12 billion totally) more than pay for all funds spent globally on IPM over time.

Having said that, this review does raise the question of whether IPM resources, especially for training, have been spent in the most cost-effective manner. Modern communication technologies have opened opportunities for rapid pest diagnosis and

IPM information transfer that did not exist even 10 years ago. They also provide more alert farmers the opportunities to alter the design of their cropping systems to more sustainably manage their pests. Most impact assessments of IPM in developing countries have focused on the economic benefits of adding IPM practices to current farming systems as opposed to more radically altering them. System-wide impact assessments would be challenging but are conceptually possible.

The toolbox of IPM practices has never been fuller of alternatives for managing specific pest problems, at least in the short run. The need for additional economic impact assessments of IPM has grown because decision makers increasingly seek information on returns to alternative investments. Quality impact assessments can be difficult to conduct, as they require at least some knowledge of the subject being evaluated and require careful attention to address potential evaluation pitfalls such as selection bias. But documenting returns on public investments in IPM may be essential for its continued support.

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9

The Roles of Soft Technologies and Cooperative Extension in Solving Wicked Integrated Pest Management Problems

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Although the integrated control concept introduced by Stern *et al*. (1959) has been considerably enriched since its inception, farmer adoption of this model in United States (US) agriculture has fluctuated (Ehler, 2006). While others have relegated the future of integrated pest management (IPM) to perceived idealistic or realistic viewpoints, we consider the themes of this book – economics and human behaviour – and explore the future of agricultural IPM in the US. Specifically, in the successive 60 years after the formal introduction of this concept, we will document some astounding success in the adoption of IPM, as well as challenges and complications. We posit that IPM is influenced by both the availability and implementation of hard and soft technologies and argue IPM implementation is most successful when both types of technologies are fully integrated and work in concert.

Technology can be classified as 'hard' or 'soft', but realistically most tactics are a combination of the two extremes. Essentially, soft technologies are handled by people and hard technologies do not require human oversight. An example of a hard technology is seed planted for a crop. This seed itself is not technology, but becomes one through breeding efforts directed towards maximum yield in a given environment. Furthermore, the hard technology of this seed developed for maximum yield can be supported through the use of various soft technologies (e.g. sampling methods and economic thresholds). Dron (2013) reviews several definitions, and says, 'soft is hard, and hard is easy'. Depending on the perspective of the user, soft technology requires creative thought and decision making in order to make them work successfully. Adding layers without replacement often softens a technology. Conversely, hard technology requires less decision making by humans. Hard technologies are less flexible and can be challenging to make changes. There are many examples of soft and hard technologies in the IPM world.

Ehler (2006) noted there were at least 65 definitions of IPM. There are now more, and the interpretation will continue to evolve. Many IPM definitions focus on elements that make up IPM (input characteristics) rather than the intended impacts of IPM (output characteristics). The US Department of Agriculture's (USDA) federal IPM roadmap (USDA, 2018a) shifts the focus from input characteristics to output characteristics. In short, it focuses on risk reduction, including economics, the environment and society (e.g. human health and social welfare). Therefore, this interpretation will serve as a framework for our discussion of agricultural IPM adoption, as it has occurred or will occur on the farm, where IPM is described as 'a sustainable, science-based,

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decision-making process that combines biological, cultural, physical and chemical tools to identify, manage and reduce risk from pests and pest management tools and strategies in a way that minimizes overall economic, health, and environmental risk' (USDA, 2018a).

Ever since the description of problems in social policy planning as 'wicked' (Rittel and Webber, 1973) there has been debate about the nature of wicked problems and what we can learn from them, spanning topics as diverse as business (Camillus, 2008) and pest management (Ervin and Jussaume, 2014; Barrett *et al.*, 2017; Harker *et al.*, 2017). In total, Rittel and Webber (1973) describe ten characteristics of wicked problems. Briefly, wicked problems are characterized by solutions that are unclear, complicated and not immediate; these problems also lack criteria that indicate when the problem is solved, lack opportunities for trial and error, and are problems that are unique. Wicked problems are difficult, if not impossible, to solve, because of the shifting nature of the problem and the possible approaches to solve them, which in turn can cause additional problems; moreover, they are wicked because of the social context where the problem is not understood until after a solution is formulated. Others have creatively addressed wicked problems with insights and principles for 'taming' a wicked problem. Ten principles of land use policy (Sayer *et al.*, 2013) have been suggested as helpful in addressing wicked problems (Jussaume and Ervin, 2016). Within these, there are implications for technical approaches to pursue. Gould *et al.* (2018) suggested that wicked evolution of resistance in insect and weed pest management is a result of a mixture of ecological, genetic, economic and socio-political factors. We conclude that what emerges in any discussion of wicked problems is the social context and transdisciplinary nature of any potential solution.

IPM is usually developed within the disciplinary technical and supporting sciences (e.g. entomology, plant pathology, weed science). But IPM is practised by people with diverse values, cultures, attitudes, knowledge, behaviours and goals, and even these can fluctuate over time and as economics (e.g. crop prices) fluctuate. Science and industry have accelerated the development and efficacy of the tactical approaches possible, but without a concomitant acceleration in our ability to address the social and transdisciplinary needs of the diverse stakeholders participating in IPM. In short, the emphasis on 'hard' technologies (those products representing pre-orchestrated solutions (Dron, 2013) like seeds, traits and chemicals) has outstripped efforts to develop the 'soft' technologies, the human-mediated, knowledge-based systems that support the integrated solutions needed (Jin, 2002). Notwithstanding the many failures and shortcomings attributed to implementations of IPM, IPM inclusive of the transdisciplinary needs of its stakeholders is the only rational strategy for addressing 'wicked' as well as 'tame' pest management problems. Throughout this chapter, we will provide examples that support this hypothesis.

IPM Complications

We wish to provide a balanced perspective of IPM, focusing on how it is practised in the US. Because we suggest that IPM works best when hard and soft technologies are utilized in concert, this section will provide examples of complications where soft technologies were not developed or not optimally deployed to complement hard technologies for IPM. These examples focus on the shortcomings of soft technologies primarily because it is more common for these to be deficient rather than the hard technologies. Towards this effort, we will focus on two themes: (i) industry-wide adoption of single tactic leading to overdependence, and (ii) behaviours of consumers and producers. While there are other complications for IPM, these themes are largely agreed upon as problematic for IPM, but are rarely viewed together through the lens of hard and soft technologies.

Industry-wide adoption of single tactic leading to overdependence

In this section, we explore the phenomenon of overdependence. Two of these examples focus on genetically engineered crops, herbicide-resistant and insecticidal crops, while the other two examples focus on prophylactic control using insecticidal seed treatments and insecticidal foliar sprays. The first two are design decisions and the latter two are control decisions (Chapter 1). All of these examples are similar, in that the hard technology is implemented before, or very soon after, the pest interferes with the crop. In a sense, all these examples could be considered prophylaxis. However, we wish to use prophylaxis *sensu strictu* to mean a control tactic employed in a crop prior to the economic threshold being reached that could have been effectively applied once the economic threshold was met. Using this definition, genetically engineered crops and other considerations of design fall outside the scope of prophylaxis. Furthermore, all these examples are similar in that soft technologies were not developed, or mismatched with the hard technologies, prior to major problems arising.

Genetically engineered crops

Glyphosate-resistant crops

When the hard technology of using glyphosate-resistant crops was first commercially planted in 1996, some academics, farmers and those in industry thought the potential for development of resistance was low. Hence, relatively little effort was put into the soft technology upon deployment. Glyphosate had already been used worldwide for over 20 years and not a single case of resistance had been documented. To some, the risk of developing resistance to this herbicide seemed unlikely, because it was the only mode of action that inhibited EPSP synthase (an enzyme important to synthesizing certain amino acids), selection pressure was low (prior to commercialization of glyphosate-resistant crops) and the potential molecular pathways for resistance were thought unlikely to evolve. Additionally, glyphosate binds to soil particles; hence, resistance-accelerating, sub-lethal doses are unavailable to emerging weeds. Finally, some assumed glyphosate would be used sparingly, since the amount and frequency of applications were limited in the initial herbicide-resistant crops. Indeed, it was even suggested that the increased use of glyphosate due to the advent of glyphosate-tolerant crops would be a positive, since it would kill weeds that might develop resistance to other herbicides (Bradshaw *et al.*, 1997).

Farmers quickly adopted glyphosate-resistant crops because many troublesome weeds could be more easily and cheaply controlled using this broad-spectrum herbicide. From 1996 to 2008 in the US, adoption of this hard technology rose from less than 5% of soybean (*Glycine max*), cotton (*Gossypium hirsutum*) and maize (*Zea mays*) fields to over 90% for soybean and over 60% for cotton and maize (Duke, 2018). Farmers also perceived this as a cost-effective option, relative to other herbicides or tillage, which was true in the short term. When profit margins are tight, farmers are hesitant to diversify to options that are more expensive in the short term. Glyphosate also made conservation tillage easier (Locke *et al.*, 2008). Widespread farmer adoption of glyphosate also forced the manufacturers of other herbicides to decrease prices to remain competitive, which was exacerbated when glyphosate went off patent (Nelson and Bullock, 2003). Although other herbicides were used to varying degrees in field crops, 10 years after the introduction of glyphosate-resistant crops, glyphosate was the most widely used herbicide in the US and the world (Duke, 2018). Furthermore, given the excellent environmental and human health profile of glyphosate compared with other herbicides (Dill *et al.*, 2008), the use of glyphosate on glyphosate-resistant crops seemed to be the panacea for weed control to some.

Others expressed concern over the development of resistance due to dramatic increases in selection pressure. While these concerns were noted, efforts to diversify to other hard technologies and/or to develop the knowledge-based, soft technologies to create complementary tactics were minimal. In fact, investments into research and development of other herbicides were shifted to investment in the development of seeds and traits due to the meteoric success of glyphosate (Charles, 2001; Duke, 2005). More than 20 years after the first commercial plantings of glyphosate-resistant crops in the US, glyphosate usage dominated in terms of areas treated, longevity in effectiveness among widely planted crops and in application amount compared with other herbicides (Benbrook, 2016; Duke, 2018).

Today, it is no surprise there have been 300 separately reported individual cases of resistance to glyphosate in 40 species worldwide (Heap, 2018). Unfortunately, where weed resistance to glyphosate was widespread, farmer profits suffered (Wechsler *et al.*, 2018). Furthermore, as weed resistance to glyphosate increases, its use will decline (Duke, 2018), and the resulting increase in herbicide applications will likely result in an additional reduction in farmer profitability. Moreover, while some predict that conservation tillage will likely decline (Duke, 2018) with negative environmental impacts (Shaner *et al.*, 2012), in the short term, farmers will adopt genetically engineered crops tolerant to other types of herbicides (Green, 2018) and will face the same issues of overdependence (Gould *et al.*, 2018). The failure of society through industry, government or education to shift the burden of this negative externality (reduced performance as a consequence of lost susceptibility to glyphosate in weeds) directly to farmers in order to better monetize the risk of overreliance on glyphosate has led to the predictable outcome of reduced profitability of row-crop production and sharp increases in the costs of weed control. While many recognize the need for multiple tactics and the importance of soft technologies, such as social science (discussed later, in part, under common pool resources), in weed control systems (e.g. Gould, 1995; Frisvold *et al*., 2009; Erwin and Frisvold, 2016), overreliance on a single control tactic remains a wicked problem (Gould *et al*., 2018).

Insecticidal crops

Broad-scale use of genetically engineered insecticidal (Bt) crops to control many target pests has been successful in reducing insect damage and their overall abundance. For example, *Ostrinia nubilalis* was once a widespread insect pest of maize in the US Corn Belt. However, the widespread adoption of Bt maize has reduced abundance of this pest, increasing farmer profitability in the region (Hutchison *et al*., 2010), without a single documented case of resistance to this pest. Moreover, there was a spillover effect: farmers who planted non-Bt maize benefited from those who planted Bt maize, due to the area-wide reduction of *O. nubilalis* densities. Similar results have been documented for *Helicoverpa zea* abundance and associated impacts in vegetable crops (Dively *et al*., 2018) and for *Pectinophora gossypiella* in Arizona cotton (Carriére, 2003), which was ultimately declared free from this pest in the US and northern Mexico (USDA, 2018b; Anderson *et al*., 2019). However, in contrast to *O. nubilalis* or *P. gossypiella*, *H. zea* has developed resistance to Bt cotton (Cry1Ac (Tabashnik *et al*., 2013; Tabashnik, 2015) and Cry2A (Reisig *et al*., 2018)) and Bt sweetcorn (Cry1A.105, Cry1Ab and Cry2Ab2; Dively *et al*., 2016) in the US.

This resistance (*sensu* Tabashnik and Carriére, 2017) developed, in part, because other support tools were not used to their full capability as part of an IPM system with Bt crops. For example, the speed of resistance evolution to insecticides is negatively correlated to selection pressure. In Bt maize, one way that selection pressure is decreased is by planting non-Bt maize to serve as a refuge for the production of Bt-susceptible insects. Notably, this refuge works best when the toxin dose of Bt is high, which it is not for the Cry toxins in maize for certain pests, such as *H. zea* (Tabashnik *et al*., 2013). Additionally, refuge maize plantings in the Midwestern US began decreasing over time around 2005 (Jaffe, 2009) and label-mandated, refuge compliance was even lower in the cotton-producing states of the southern US (Reisig *et al*., 2017). Furthermore, there are more growing degree-days in southern latitudes, with more generations produced compared with northern latitudes. Finally, both Bt maize and Bt cotton are grown in the southern US. Based on these factors, non-Bt crop refuge is most important for *H. zea* in the southern US where it is planted the least!

At the heart of pesticide use lies a tension and overlap among desires for (i) regulatory agencies to minimize environmental and human health risk; (ii) hard technology providers to place a highly effective product across a wide geography; and (iii) farmer goals to minimize economic risk from pest losses. In the southern US, the current situation is further complicated by the cross-crop impacts of *H. zea* hosts, including maize (a Bt crop), cotton (a Bt crop) and soybean (a non-Bt crop). In this region, Bt maize is effective against a wide suite of lepidopteran insects, many of which are present only sporadically (Reisig *et al*., 2015b; Reay-Jones *et al*., 2016). *Helicoverpa zea* commonly infests maize in this region, and is a target of Bt maize, even though it does not cause yield loss in maize that is planted on time (Bowen *et al*., 2014; Reay-Jones and Reisig, 2014; Bibb *et al*., 2018). In contrast, *H. zea* can severely limit cotton yields. Southern US maize farmers are still worried about losses in maize due to other lepidopteran insects. Weather conditions are not always optimal for timely planting, and sporadic pests, such as *Spodoptera frugiperda*, can cause more widespread yield loss in outbreak years and in late-planted maize. Also, mycotoxin concentrations in harvested maize are sometimes correlated with lepidopteran damage, although associations are not consistent (Abbas *et al*., 2013). Finally, the maize seed-producing industry places more advertising emphasis on Bt hybrids, compared with non-Bt hybrids (Reisig and Kurtz, 2018). Together, the factors mentioned in this paragraph place downward pressure on the planting of non-Bt refuges.

To complicate the issue, the generation of *H. zea* prior to the generation that infests cotton is mostly produced in maize. Unlike maize, however, *H. zea* can be a major yield-limiting pest of cotton, in severe cases leading to complete yield loss. However, despite its destructive potential in cotton, very few of the *H. zea* that feed on cotton, pupate and emerge as adults contribute to the overall population of *H. zea* in this region. Rather, other hosts, likely maize and soybean, are more important contributors to the overall population structure (Head *et al.*, 2010). Although soybean is not a Bt crop in the US, both maize and cotton are. Since so many more *H. zea* are likely produced in maize compared with cotton, Bt cotton farmers do not plant non-Bt cotton as a refuge in the southern US. Furthermore, soybean and other wild hosts serve as refuges as well. Thus, farmers who plant non-Bt maize essentially give Bt cotton farmers a free ride in relation to resistance management (this is termed 'freeloading' and will be covered later under common pool resources). This is further compounded by the factors mentioned previously – the de-emphasis on non-Bt maize marketing and the perceived risk from less common lepidopteran pests in maize. Since the price of non-Bt hybrid seed is generally lower than Bt seed, some southern US maize farmers who have experienced *H. zea* resistance in Bt maize are demanding more non-Bt hybrids. This is ironic, since the adoption of Bt maize facilitated the decline of major yield-limiting insect maize pests in this region and since many of these farmers were reluctant to plant refuge maize in the past.

Bt cotton faces a further challenge in this region. In both Bt cotton and Bt sweetcorn, foliar insecticide use targeting *H. zea* initially declined (Dively *et al.*, 2016; Fleming *et al.*, 2018). However, foliar sprays for *H. zea* in these crops have increased as a result of Bt resistance (Dively *et al.*, 2016, Reisig *et al.*, 2018). Prior to the introduction of Bt cotton in the southern US, *Heliothis virescens* and *H. zea* were major pests controlled with broad-spectrum insecticides. Bt cotton was very effective on *H. virescens*, but some Bt cotton fields arguably still required foliar insecticide applications for *H. zea* to achieve maximum profitability. Prior to Bt resistance, the number of insecticide applications for *H. virescens* and *H. zea* declined in cotton, while the number of insecticide applications targeting piercing sucking insects, such as *Lygus* spp., pentatomids and thrips, increased. Both thrips and *Lygus* can be early-season pests in this region, and *Lygus* and pentatomids are mid-season pests. Although some selective insecticides can be used for these pests, the most common insecticides used for these pests are broad spectrum.

Natural enemy abundance is similar in unsprayed non-Bt cotton and unsprayed Bt cotton. However, natural enemies are harmed by typical foliar insecticides (Naranjo and Ellsworth, 2009a). Therefore, natural enemy abundance is likely very low in Bt cotton treated with broad-spectrum insecticides targeting these piercing sucking insect pests. Hence, the use of broad-spectrum insecticides during both the early and mid-seasons of cotton is reducing natural enemy abundance and exacerbating *H. zea* populations in Bt cotton.

In hindsight, many now recognize the importance of Bt crops as a part of the IPM system, rather than a single hard technological tool that can be relied on independent of other inputs. Soft technologies to increase refuge compliance are being developed (e.g. Brown, 2018, covered later in this chapter) and the hard technology of blended refuge (mixed planting of non-Bt and Bt varieties in the same field) is being considered for the southern US to ensure refuge compliance (Pan *et al.*, 2016; Reisig and Kurtz, 2018).

Prophylactic control

Prophylaxis is not always unwise or incompatible with IPM. In certain pest and crop combinations, there are occasions where prophylaxis is the most profitable solution. This will be discussed in a later section. However, there are other situations where the benefit of prophylaxis is unknown. In our experience, insecticides are used prophylactically in situations when the farmer (i) does not have easy, accessible, precise sampling tools or good pest forecasting tools (hard technologies when viewed as the physical tool (e.g. a sweep net, pheromone trap or weather report), but soft technologies when used in pest management); (ii) does not have adequate knowledge of the pest(s) in question (soft technology); and (iii) does not have good non-prophylactic control options (hard technologies). Note that only one of these conditions may be present for farmers to choose prophylaxis, but several are often present. For any control intervention, including prophylaxis, the value of the crop protected must exceed the cost of that intervention. However, as crop prices increase, farmers usually increase inputs, including protective ones, such as insecticides, to manage risk on their investment. Hence, the prophylactic use of insecticides is often associated with high crop prices, but not always.

Seed treatments

In the case of insecticidal seed treatments, a large proportion of field crop seeds (e.g. maize, cotton, soybean and wheat) are treated before planting, despite the fact that 'most fields in most growing seasons will not be under major pressure from a particular sporadic pest' (Papiernik *et al.*, 2018). The case of maize is particularly extreme, where nearly all US seed is treated prior to purchase by the farmer (Douglas and Tooker, 2015); insecticidal seed treatment use in cotton is similar and will be discussed later. It is unlikely that the adoption of these prophylactic insecticides in maize was due to an increase in crop value or incidence of seed/seedling pests (Douglas and Tooker, 2015), although in some cases they can increase profitability (e.g. Gaspar *et al.*, 2015; North *et al.*, 2016, 2018a, 2018b) or are perceived to increase profitability (Hurley and Mitchell, 2016). Rather, farmers perceive insecticidal seed treatments in these crops as an economic risk mitigation tool (Chapter 1), and the agrochemical and seed industry can provide insecticidal seed treatments with relatively low use rates that are highly effective and inexpensive to produce. Furthermore, little is known about soil-dwelling pest biology in many of these crops and sampling is difficult (Papiernik *et al.*, 2018). Therefore, farmer acceptance of insecticidal seed treatments in many crops is likely a reflection of aversion to economic risk. Also reflective of this uncertainty is a general disagreement among US Cooperative Extension scientists as to when farmers should use insecticidal seed treatments.

In south-eastern US cotton, insecticidal seed treatments are a key hard technology used in the cotton IPM programme, with economic risk aversion playing a major role in farmer adoption. However, their maximal benefit has been eroded from a loss of an important hard technology (aldicarb), and a lack of adequate soft technology. Nonetheless, recent soft technological advances have bolstered their effectiveness.

The potential risk of economic loss to cotton from thrips (Thysanoptera) is high and thrips are some of the costliest insect pests in this region. Economic injury levels for these pests are low, are likely to be exceeded in the majority of cases and timing post-planting control interventions can be challenging. Therefore, insecticidal seed treatments provide the basis for thrips control. Thrips can cause early season injury to seedlings that can translate to loss of apical dominance, maturity delays, reduction in biomass and yield loss (Cook *et al.*, 2011; Herbert *et al.*, 2016). They are difficult to sample due to their small size and thigmotactic behaviour within the developing leaves of cotton seedling terminals. Adult thrips colonize plants just after emergence and oviposit into cotyledons (D'Ambrosio, 2018). If growing conditions are cool, cotton seedlings grow slowly and, in these conditions, damage can be severe from only a few larval thrips feeding on cotton leaves before they are fully expanded.

Most farmers in this region have adopted this prophylactic approach, using at-planting insecticides. As mentioned previously, thresholds in this region are low and almost always exceeded in the region; for example, in North Carolina, the threshold is approximately 25% or more of the plants showing significant damage and an average of two or more larval thrips per plant (Bacheler and Reisig, 2015). Additionally, foliar insecticides can be effective, but are most effective when timed properly, when the first true leaf is just emerging effectively killing larvae emerging from eggs laid in the cotyledons (D'Ambrosio, 2018). In certain conditions, missing this timing by even a few days can allow thrips to economically damage the seedlings. Moreover, the damage potential from thrips is highly dependent on moisture and temperature. When conditions are cool, cotton plants cannot outgrow damage from thrips. Furthermore, the early-season vigour of varieties is also important. Among commercially available cotton varieties, immature thrips densities and the damage they cause to the plant varies widely (Kerns, 2018). Hence, economic risk for cotton farmers can be as unpredictable as the weather. Finally, to maximize economic efficiency, farmers must balance their time and equipment. Therefore, farmers try to have enough equipment to make applications in conditions that can range from fair to challenging. If fields are wet, for example, ground applications can be impossible to make and aerial applicators are in high demand, with prices that reflect this demand. As a result, most cotton farmers prefer to use at-planting insecticides that have persistent efficacy through the most thrips-sensitive growth stages of the cotton seedling.

The backbone of the at-planting insecticide programme was once a carbamate, aldicarb, applied in the soil at planting. In many regions, aldicarb minimized economic losses due to thrips and was more effective and economical than other insecticide control options. For example, insecticide costs plus losses from thrips were calculated across 25 replicated trials in North Carolina and Virginia (2001–2011). Relative to cotton planted with aldicarb (the gold standard at the time), costs plus losses for cotton planted with a neonicotinoid seed treatment plus a post-emergence foliar insecticide spray were $82/ha higher, cotton planted with a neonicotinoid seed treatment was $151/ha higher and cotton planted without any insecticide was $635/ha higher (J.S. Bacheler, North Carolina, and D.A. Herbert, Virginia, 2011, personal communication). Furthermore, more cotton had to be treated for other pests, *Aphis gossypii* and tetranychid mites, later in the season following an insecticidal seed treatment compared with aldicarb.

Abruptly, the manufacturer discontinued aldicarb production during 2011. The removal of this hard technology in the system forced farmers to rely on other hard technologies, with very few soft technologies to support their use. In general, the hard technology of insecticidal seed treatment became nearly universal in south-eastern US cotton, sometimes supported with foliar insecticide applications. In an attempt to mitigate the yield lost to thrips from the replacement of aldicarb with a less effective hard technology, other hard technologies were explored. For example, the hard technologies of soil applications of various insecticides, in combination with insecticidal seed treatments were explored as options to protect cotton yield (Spivey, 2014; Herbert *et al.*, 2015; Reisig *et al.*, 2015a). In addition, cultural tactics such as at-planting fertilizer, irrigation (to increase seedling vigour and to stimulate damaged plants to compensate) and tillage were investigated (Toews *et al.*, 2010, 2013; Smith *et al.*, 2012; Reisig *et al.*, 2014). While many of these hard technologies were successful to varying degrees, they were not well supported with soft technology to spur their use. For example, while cultural technologies such as reduced tillage (Olson *et al.*, 2006; Toews *et al.*, 2010), can be effective to reduce thrips damage, farmers are hesitant to make cultural changes for insect management, because doing so often has easily predicted short-term implications (e.g. increased herbicide use, yield loss from factors other than thrips, changes in soil water holding capacity, cooler soil planting temperatures in the spring) and might require specialized equipment (e.g. a planter modification for no-till).

Unfortunately, the widespread use of these insecticidal seed treatments in both cotton and soybean likely contributed to evolution of resistance to the main class of insecticides used in cotton insecticidal seed treatments, neonicotinoids (Huseth *et al.*, 2018), in the main pest thrips species, *Frankliniella fusca* (Stewart *et al.*, 2013). In response to this resistance, Cooperative Extension scientists in the region were left without good alternative control tools to recommend, and farmers in this region increased the amount of insecticides applied at planting in soil as well as applied to foliage after the cotton emerged.

In response to these challenges, a tool was developed to predict when thrips will disperse from hosts. This model uses weather (both temperature and moisture) to predict cotton seedling susceptibility and thrips development and dispersal to determine the potential risk to cotton seedlings based on planting date in specific cotton fields (Kennedy *et al.*, 2016). This soft technology complemented and guided the use of hard technologies. Thus, Cooperative Extension scientists were able to promote the tool as a way to target in-furrow or foliar insecticides for thrips in the highest risk areas only. As an example, independent crop consultants tend to be early adopters; in North Carolina, during the first year of this tool's launch (2017), nearly half of them used the tool and nearly two-thirds of them had adopted the tool by 2018. Adoption of this tool is still growing and is helping farmers improve their use of insecticides targeting thrips.

We can use this example as a lens through which to view the importance of soft technologies to use insecticidal seed treatments more effectively. The concept of effectiveness should include factors such as delaying resistance, minimizing economic risk for the farmer and return on investment for companies that sell the seed treatment. These factors can be at odds with one another. For example, resistance can be delayed by minimizing selection pressure and avoiding use of insecticidal seed treatments, but this would come at the expense of increasing economic risk for the farmer and decreasing return on investment for companies. Furthermore, even if the design of the system is optimized to harmonize these factors, changes in the system can quickly impact the balance. For example, seed dealers work on the local level and are often distinct companies from the corporations that develop and produce insecticidal seed treatment. If the local dealers give a commission for applying insecticidal seed treatment just prior to the time of sale to the farmer, insecticidal seed treatment use could increase, despite the desires of the company that manufactures the insecticidal seed treatment.

In the thrips example, the extensive use of neonicotinoid seed treatments in cotton and soybean increased selection pressure after the removal of a key hard technology in the cotton system (aldicarb). However, farmers still relied on neonicotinoid seed treatments to minimize economic risk. Furthermore, not only was neonicotinoid seed treatment efficacy compromised with resistance, it was generally not as effective as aldicarb even before resistance was documented. As a result, a predictive model (soft technology) was developed to guide the use of foliar insecticides to bolster neonicotinoid seed treatments.

This begs the question as to why soft technologies were not developed before aldicarb was removed or before neonicotinoid resistance was documented? Social aspects are likely important. For example, are Cooperative Extension personnel, farmers and industry personnel willing to work together for a common goal? Additionally, Cooperative Extension personnel are reliant on funding sources that are generally more willing to fund the development of solutions to a problem once it has occurred rather than before it has occurred. Similarly, those in pest management are often constrained to work on the most pressing immediate problems at the expense of potentially longer-term problems that might emerge on an uncertain time horizon.

The story of neonicotinoid seed treatments in cotton for thrips management exemplifies the need for soft technologies to support neonicotinoid seed treatments in other crops across diverse regions. Pest diversity across species and incidence can vary widely in any given crop in a particular region. Therefore, those in pest management should first work to understand the biology of potential pests in the system. Papiernik *et al.* (2018) point out that this is unknown for many of the pests in many of the crops that neonicotinoid seed treatments target, but this knowledge is critical for decision makers and Cooperative Extension to understand the potential economic value that an insecticidal seed treatment might bring. If value can be determined, then this might help spur interest into the development of soft technologies that can assist insecticidal seed treatments to balance the interest of all stakeholders.

Foliar treatments

Farmers try to balance the cost of a management intervention and potential economic loss in a complex consideration of economic risk that is highly dependent upon the environment. Economic risk can be influenced by a number of factors. For example, farmers might choose to make a control decision based on a shorter-term time horizon, if the short-term cost is low or if the perceived economic risk is high. Moreover, one way to minimize cost is to reduce the number of equipment passes across the field. Sometimes this can be accomplished using scouting and making a pesticide intervention only when necessary. Other times, prophylactic insecticide applications can minimize cost. For example, *Oulema melanopus* is a major insect pest of wheat (*Triticum aestivum*) in the south-eastern US. Insecticides in the pyrethroid class are highly effective at controlling this insect, with a long-lasting residual. However, this insect usually reaches damaging levels after the growth stage called jointing (Reisig *et al.*, 2012). Insecticides for wheat are usually applied using ground sprayers. Driving over the wheat after jointing often reduces yield. Hence, farmers in the south-eastern US prophylactically apply insecticide before jointing to control *O. melanopus*, but only when wheat prices are relatively high. When wheat prices are relatively high, these prophylactic insecticidal sprays are more profitable on average, but potentially more costly. For example, in some situations, *O. melanopus* populations can be high or oviposition can occur later, overcoming the continually decreasing residual concentration of the insecticide. When wheat prices are relatively low, these prophylactic insecticidal sprays are almost always less profitable (Reisig *et al.*, 2012).

In this case, crop price is used as a proxy for scouting and control as a soft technology. Nonetheless, the ecology of the system could also inform management (Peterson *et al.*, 2018) and could serve as an improved soft technology to complement the hard technology. In the case of *O. melanopus*, scouting is expensive relative to the average damage this pest causes from year to year. Therefore, if scouting can be optimized, costs could potentially be reduced. Many believe this insect is more damaging when tiller density is relatively low and focus scouting on fields with low-density stands. However, even though *O. melanopus* damage is more apparent in low-density wheat stands, it actually prefers to oviposit in denser wheat stands. However, the *O. melanopus* densities become sparser since there are more tillers for any given individual insect to feed on. Therefore, even though there are more *O. melanopus* individuals in a given area of a dense wheat stand, compared with a low-density wheat stand, the density of *O. melanopus* and their subsequent damage appears higher in low-density wheat stands, since there are fewer tillers relative to individual insects (Honêk, 1991; Reay-Jones, 2012; Reisig *et al.*, 2017). South-eastern US wheat farmers plant in the fall hoping for an adequate stand in the spring and environmental factors interact with planting date and wheat variety to influence the stand density. Thus, modest adjustments to seeding rates in the fall is less influential on stand density in the spring than planting date, variety and environmental factors beyond the control of the farmer. Nevertheless, *O. melanopus* scouting could be focused on fields more at risk based on plant density and variety. Moreover, there are times when *O. melanopus* populations crash regionally due to unknown abiotic or biotic factors (Reisig *et al.*, 2017). Thus, prophylaxis could potentially be less profitable if scouting was focused and insecticides were used when necessary. Furthermore, scouting trips could be more efficient if scouts also noted the presence of diseases that could be treated with a foliar fungicide. Farmers could potentially tank mix in cases where both fungicides and insecticides were needed.

Furthermore, as an additional soft technological improvement, the threshold could be adjusted to reflect stand density. The current threshold in the south-eastern US is based on a robust dataset from a 2-year study across 26 fields, each containing plots where *O. melanopus* was allowed to feed and plots where *O. melanopus* was controlled (Ihrig *et al.*, 2001). Researchers in this study determined percentage yield loss by comparing the treated and untreated plots at each location, which ranged from very little yield loss to over 40%. A threshold was then set at 25 or more eggs plus larvae on 100 tillers (or stems; Reisig *et al.*, 2013) using values obtained from a regression analysis across the range of yield losses (Ihrig *et al.*, 2001), and also included estimates of control costs and crop value. Using this per-tiller threshold, densities of *O. melanopus* will not be estimable in a given area if stand densities vary across fields. In low-density stands, *O. melanopus* densities are overestimated compared with denser stands. This overestimation is compounded by the fact that low-density stands may have less value than higher-density stands (assuming the stand density falls below a certain threshold where yield losses exceed potential gains from inputs that can increase stand, such as lower seeding rates, increased nitrogen, multiple nitrogen applications, adjustment of planting date, etc.). While Ihrig *et al.* (2001) report taking plant stand measurements in their experiment, it is not reported. Therefore, additional studies may be needed to see if the threshold for *O. melanopus* should include plant stand measurements.

This example highlights the importance of readjusting the soft technologies to the system as conditions change both economically and environmentally. As economic conditions change in this system, prophylaxis becomes more or less profitable. Furthermore, prophylaxis becomes more or less profitable as the environment changes, for example, after certain weather events that influence plant stand or *O. melanopus* density. Both economic and environmental conditions can be difficult to predict, with risk aversion driving some prophylactic insecticide use. Hence, in this system, a threshold that could model uncertainty, changing with economic and environmental conditions that influence factors important to the impact of *O. melanopus* on wheat yield in a field of a given plant stand density, could provide farmers the flexibility needed to reduce their perceived economic risk from this pest.

Human behaviour

IPM is driven by human behaviour, both on the production side (the individual farmer) and on the consumer side. In this section, we highlight two sets of behaviours that complicate IPM: (i) consumer behaviour and preferences for certain quality characteristics, and (ii) farmer behaviour in terms of economic risk aversion, use of common pool resources, and their desire for simplicity and convenience. Several of these factors are well studied in the social sciences, but are not well studied in IPM. Furthermore, both factors could be incorporated into IPM systems, but require soft technologies to do so.

Consumer demand

IPM is ultimately carried out by individual farmers with every decision that they make relative to farming.

Because the crop is then sold, consumer demand must be incorporated into IPM, even if indirectly. For example, consumers demand high-quality, but low-priced food and fibre products, requiring farmers to efficiently produce crops to meet this demand. In this section we focus on consumer demands that have a direct impact on IPM, using aesthetics and organic and non-GE crops as examples. We define aesthetics to mean crop qualities other than those that have an impact on health (including nutrition) or yield. Finally, while we reference USDA organic, the conclusions from this section are applicable to crop products grown in a 'non-conventional' manner that satisfies a particular consumer demand or particular crop production philosophy of a farmer other than IPM (e.g. sustainable and biodynamic).

AESTHETICS. The production of fruits and vegetables requires products to be hygienic and cosmetically appealing, a standard even required by the USDA (Palumbo and Castle, 2009). Fresh produce often requires the intensive use of pesticides, often broad-spectrum ones. Incorporating alternative hard and soft technologies would allow society to accomplish other goals or avoid negative externalities in these systems. While not antithetical to IPM, the consumer demand for the unblemished appearance means these systems have the potential for needing more intensive management strategies if thresholds must be lowered to meet these demands.

For example, timothy (*Phleum pratense*) is a high-value forage crop grown in the California intermountain regions. Two markets for timothy hay are feed for horses in southern California and feed for cows fed only grasses and grains and sold as natural beef in Japan. Buyers primarily purchase hay based on aesthetic properties, such as greenness of the hay and length of the flower head, followed by price and other considerations. Both thrips (*Anaphothrips obscurus*) and mites (Tetranychidae and Eriophyidae) are associated with a decrease in aesthetics. In response, a hybrid economic injury level was developed to reflect aesthetic considerations of the buyers (Reisig *et al.*, 2009). As a result, timothy farmers in this region apply broad-spectrum insecticides to control *A. obscurus* to keep hay looking aesthetically pleasing. Unfortunately, these insecticides can flare tetranychid mites (Reisig *et al.*, 2009), leading to an environmentally and economically expensive pesticide treadmill (Carson, 1962). Moreover, the number of broad-spectrum insecticides available to these farmers is limited, in part due to limitations designed to minimize insecticide residues on hay.

Both thrips and mite infestations rarely translate into yield loss and there are no documented impacts on animal nutrition. As a result, there is the potential to move this system to a strategy less dependent on intensive pesticide use. Buyers are willing to pay more for aesthetically pleasing hay, but are likely unaware of the pesticide intensity required to produce this hay. Furthermore, natural areas and watersheds with abundant wildlife surround the area where this hay is produced and are subject to environmental degradation. It might be possible to develop soft technology and educate a subset of these buyers. Perhaps this subset might be willing to accept less aesthetically pleasing hay, especially given the lower price point of this hay and the fact that it is as nutritious to the animal as more aesthetically pleasing hay. Consumers are increasingly purchasing products they view as 'sustainable', broadly interpreted to mean having a positive environmental impact (Rudominer, 2017; Crawford, 2018). Therefore, hay buyers, Cooperative Extension, farmers and industry personnel could work together to trial this or other solutions.

Preference for organic foods and crops not genetically engineered

Many farmers who grow organic, and most farmers who grow conventional crops, do so in response to consumer demand for organic or in response to the unavailability or consumer rejection of genetically engineered crops. Both of these cropping systems can function within an IPM framework. However, this can sometimes complicate and intensify the system. For example, while the effects of herbicide-resistant traits are not as clear, in general, genetically modified insecticidal crops increase yield and decrease insecticide use (Gould *et al.*, 2016). Hence, consumer rejection of genetic engineering sacrifices the benefit of insecticide reduction that insecticidal crops can bring. Ironically, by avoiding insecticidal crops, some consumers may be exposing themselves to even higher levels of insecticide. In this case, soft technologies involving the social sciences may provide answers. Particularly, since consumer behaviour can influence organic and conventional crop production, those involved in the production of organic and conventional crops should engage with consumers.

Likewise, many consumers believe organic production involves no insecticide use or that the active ingredients of the insecticides are healthier and more environmentally friendly compared with synthetic options (Illukpitiya and Khanal, 2016). This is not always the case. For example, in a study comparing organic, IPM and conventional cotton systems, there were more total pest control materials used in organic cotton than IPM or conventional cotton (Sweazy *et al*., 2007). The amount of insecticide, herbicide and miticide active ingredients used in organic cotton production were 4.8 times higher than IPM cotton and 2.4 times higher than conventional cotton. Furthermore, since no herbicides or insecticides were used in organic production, comparing only miticide active ingredients, organic cotton production used 12.5 times more than IPM cotton and 3.6 times more than conventional cotton. This is remarkable considering the fact that periodic early-season releases of *Chrysoperla carnea* larvae (12,000 per ha) were made in both the organic and IPM treatments (Sweazy *et al*., 2007).

Similarly, while USDA organic-approved insecticides can be selective, some active ingredients can be as detrimental to natural enemies as conventional insecticides. For example, spinosad is available to organic farmers, but has both lethal and sublethal effects on *Orius laevigatus*, an important predator in European agricultural systems (Biondi *et al*., 2012). Likewise, *Orius* species are important natural enemies in the US. Additionally, many USDA organic-approved insecticides are less selective than conventional counterparts and, in some cases, equally or less effective (Bahlai, 2010). This presents a challenge to organic farmers, who often rely on a suite of hard technologies, such as natural enemy releases, banker plants (plant species grown specifically to enhance natural enemy populations), intercropping and adjustment of planting dates, to maximize profitability. Unlike insecticides, which are broader spectrum, the specific suite of these alternative interventions tend to be specific to each farm and are often the result of a trial-and-error process. Therefore, the lack of generalization renders the development of soft technologies to support use across systems difficult.

Farmer behaviour

ECONOMIC RISK AVERSION. In some cases, the economic parameters that underlie thresholds do not take uncertainty into account. In these cases, there may be paltry scientific information on a problem or it may be a wicked problem that has not been tamed or cannot be tamed. Farmers use insecticides, not only to maintain yield potential, but to manage economic risk. In some cases, insecticide use can increase economic risk (e.g. if the price of the crop drops at harvest time or if an insecticide application flares secondary pests). In other cases, insecticides can decrease economic risk. In this case farmers may choose to use a pesticide, because they are uncertain if the outcome will be negative if they do not (e.g. when insect numbers are below the economic threshold or by using a broader-spectrum pesticide than necessary). Examples include uncertainty about pest density, yield loss per pest and pesticide effectiveness (Pannell, 1991).

COMMON POOL RESOURCES. Public goods (like insect susceptibility or water quality) can be non-excludable: anyone can consume them, and therefore, everyone has access to them. They are just like the air we all breathe. However, unlike the air that we breathe, insecticide susceptibility (Miranowski and Carlson, 1986; Mitchell and Onstad, 2014) or water quality are rival public goods, where individuals that consume these goods do so at the expense of others. As another complication, even when solutions are put into place to manage common pool resources, some may continue to use the resource inappropriately at the expense of others, known as freeloading.

One example used earlier was that of non-Bt refuge. In the US, farmers who plant Bt maize must plant some portion of their farm to non-Bt maize (refuge) to slow the evolution of Bt resistance, a requirement mandated by the government. Resistance is delayed in this way, since Bt-susceptible pests develop in refuge crops and can mate with any potentially resistant pests that are able to develop in the Bt crop. However, non-Bt refuge plantings have decreased since Bt crops were first commercialized and are planted by only a minority of farmers in some parts of the US (Reisig, 2017). This is not surprising because pest susceptibility to insecticides, i.e. the Bt toxin in insecticidal crops, is a common pool resource (Gould, 1995) and contributes to pesticide resistance being a wicked problem (Gould *et al*., 2018).

Others have recognized the potential for those outside the governmental regulatory agencies to help with resistance management and have suggested that the coordination of farmers, governmental authorities and industry in Australia has contributed to effective resistance management (Carrière *et al.*, 2019). While recent US industry and Cooperative Extension-based efforts to inform farmers on the importance of non-Bt refuge have been ineffective to increase refuge plantings (Reisig, 2017 and references therein), an industry-based campaign using moral suasion provided promising results (Brown, 2018). Importantly, examples of successes in solving common-pool resource problems often involve community-based initiatives (Ostrom, 1994). The industry-based moral suasion campaign combined both moral suasion and community-based incentives. While a previous effort to increase non-Bt refuge focused more on the economics of the problem (i.e., smaller-sized farmers with less capital and income tended to plant less non-Bt refuge; Reisig, 2017), results from the moral suasion campaign support the argument that other sociological factors may be important as well. For example, Ervin and Jassaume (2014) argue that having an understanding of the demographic and human capital characteristics of farmers that are early adopters of technology, having an understanding of their community ties, having an understanding of their social networks, as well as having an economic understanding are critical for solving common pool resource problems. Managing a target pest in insecticidal crops without increasing resistance is a wicked problem (in this case using non-Bt refuge plantings). Therefore, future efforts to create an effective soft technology framework should capitalize on these results to involve the entire community of industry, farmers and Cooperative Extension.

VALUING SIMPLICITY AND CONVENIENCE. Farm sizes in the US are increasing over time. Increasingly, farmers have to rely on the judgement of others for pest management decisions. Pesticide application equipment size and complexity has increased in tandem with farm size, and fewer decisions are made on a field-by-field basis. On large farms, pesticide application prescriptions are often made to cover every field of the farm to be timely and to minimize complexity. Even in cases where pesticide applications are made on a field-by-field basis, fields with sub-threshold-level pests are often sprayed to avoid the costs associated with potential follow-up applications, should these fields exceed threshold. To be clear, we are not suggesting that single fields are the unit of measurement requisite for IPM, but rather that farmers generally use these as units of measurement. In some cases, even when only a subset of these fields reach threshold, an insecticide application or alternative intervention is made across all fields. To make this decision, farmers must weigh the costs of waiting for an application, which may include additional scouting, potential for application delay due to weather, potentially increased cost in insecticide due to shortages or lack of bulk discounts, time to prepare sprayer and travel to fields, etc. Although they could be, usually such considerations are not built into thresholds.

Most pest management recommendations are for the average farmer in a given geography. While this is expedient and simple for an average farmer, distribution around the average can vary. That is to say that, the response in crop yield for some pest management scenarios is predictable and many farmers can adopt the same tactic to achieve good control. In contrast, the response in crop yield for other pest conditions is highly dependent on other factors (e.g. weather, crop variety planted, soil type, planting date, etc.). In these more unpredictable situations, farmers need to weigh multiple factors when making management decisions. Furthermore, farmers, consultants and scouts often demand simple straightforward pest management recommendations. Therefore, it can be difficult to bridge the gap between the inherent complexities of the system and the desire for simplicity in pest management recommendations.

IPM Successes

In this section, we wish to provide two contrasting examples of IPM successes that support our position that IPM functions best when hard and soft technologies are harmonized. The first is an example of a nascent IPM programme for *Aphis glycines* in Midwestern US soybean, while the second is an example of a mature IPM system in Arizona cotton. Both examples involve invasive pest insects and crops that are grown on a wide area. However, the soybean example provides an example of how soft technologies can complement a handful of hard technologies (insecticidal seed treatment, foliar insecticide application and resistant varieties) when an invasive insect pest disrupts IPM in a single crop across a broad landscape. In contrast, the cotton example provides an example of a disrupted system with multiple pests, multiple crops and multiple hard technologies that was stabilized through the development and successful implementation of soft technologies.

A nascent IPM success example

Aphis glycines is an invasive aphid to North America, first confirmed in 2000. This species has multiple, overlapping generations every year and can be found feeding on soybean for over 90 days. Before 2000, soybean in the Midwest rarely required foliar insecticides, as the plants tolerated defoliation and pests were infrequent. After its introduction, *A. glycines* quickly became the most economically important insect pest of soybean in the north central region of the US, changing the relatively low frequency that soybean was sprayed with insecticide in this region. During outbreaks, *A. glycines* can reduce seed size, seed weight and yield by 40% (Ragsdale *et al.*, 2007). In some locations of this region, aphids need to be managed every year to avoid yield loss. But throughout most of the Midwestern states, aphid outbreaks are erratic, with outbreaks occurring much less frequently.

As a result of the potential negative impact on yield, the hard technology of foliar insecticides was quickly adopted by farmers. Pyrethroids and organophosphates were the most commonly applied classes of insecticides, and good knockdown was expected with a proper application (i.e. high volume and pressure to create droplets that contacted the aphids). Also, university entomologists conducted research to understand the biology, life cycle, scouting and management of this pest (Tilmon *et al.*, 2011; Hodgson *et al.*, 2012) to assist in the development of soft technologies. Additionally, an economic injury level and economic threshold for foliar applications were developed (Ragsdale *et al.*, 2007), and continue to be validated with small-plot research (Koch *et al.*, 2018). Although farmers were urged to rotate modes of action to delay resistance (Hodgson *et al.*, 2012), soft technologies have not been developed to support the implementation of this recommendation.

In some cases, aphids colonize soybean during the early vegetative stages, but are likely to move within and between fields after soybean bloom in mid-July. Insecticidal seed treatments became available in 2003, which can reduce the population growth of aphids. However, most university research showed insecticidal seed treatments are not effective tactics to protect yield (Krupke *et al.*, 2017). Although they can prophylactically control *A. glycines* during the early season (Magalhaes *et al.*, 2009), up to 42 days after planting (McCarville and O'Neal, 2013), this time period of control is generally not long enough to influence yield, given the compensatory nature of soybean plants and other influences on yield during the growing season.

Soybean breeders have been successful at developing multiple host plant resistance genes for *A. glycines* (Zhang *et al.*, 2017), and pyramided varieties (two or more resistance genes expressed at the same time) reduce the likelihood of needing a foliar insecticide in August, when aphids typically reach the economic threshold. To date, host-plant resistance is available in non-herbicide tolerant varieties, but the adoption rate is <1%. If host-plant resistance use increases and insecticide use decreases, it may provide a more suitable habitat to also encourage biological control of *A. glycines*. To date, natural enemies can impact aphid populations, particularly early-season colonization (Costamagna and Landis, 2006), but do not significantly contribute to current aphid management because of farmer reliance on foliar, broad-spectrum insecticides (Hodgson *et al.*, 2012).

Aphids in other crops have a history of developing resistance to insecticides, and the agrochemical industry is interested in developing new modes of action for *A. glycines*. As of 2018, there were multiple options labelled for this pest, including sulfoxaflor, pyrifluquinazon, afidopyropene and flupyradifurone. In most cases, the efficacy of these insecticides is comparable with pyrethroids and organophosphates (Hodgson and VanNostrand, 2019), but they are more expensive to use (4–6 times the cost of generic pyrethroids). New modes of action will become more attractive to use as resistance to older insecticides continues to evolve and worsens (Hanson *et al.*, 2017), or if these older materials are restricted or eliminated in the US because of environmental or human health concerns.

The long-term approach for managing *A. glycines* should include a combination of hard and soft technologies. For example, although farmers currently avoid using insecticides that are not pyrethroids or organophosphates due to price, research could be done to support soft technology highlighting the selective benefits of the newer modes of action. These insecticides are not only highly effective, but many harm a narrower spectrum of species.

While secondary pest outbreaks are less of a concern in Midwest soybean compared with southern latitudes, other tools could be used in concert with these insecticides, such as implementing host-plant resistance into high-yielding, herbicide tolerant, soybean varieties. This will reduce the overall effect of foliar insecticides on the landscape and delay the formation of resistance to multiple insecticide groups. Scouting and timely foliar sprays when aphids exceed the economic threshold will improve profit margins, particularly in years when rescue treatments are not needed.

A mature IPM success example

In Arizona, the agricultural industry faced catastrophic losses to pink bollworm (*Pectinophora gossypiella*), a cotton specialist, and the silverleaf whitefly, an invasive crypto-species of the *Bemisia tabaci* complex that simultaneously destabilized pest management in cotton, melons, vegetables and ornamentals in the early 1990s. Today two and half decades later, the pink bollworm has been successfully eradicated from all of the US and northern Mexico (USDA, 2018b; Anderson *et al.*, 2019) and the whitefly has been relegated to a routinely managed (and understood), key pest of the system. This remarkable accomplishment was achieved through progressive investments in research, education and outreach to engage, develop and deploy adaptive IPM programmes with high degrees of trust, transparency and participatory engagement of a broad set of stakeholders to the agricultural industries of Arizona.

As an existential threat to the autumn produce and cotton industries, the story of IPM in Arizona is best told through the lens of IPM targeting the whitefly problem (Fig. 9.1). Elements of integrated control (*sensu* Stern *et al.*, 1959) of whiteflies were first implemented in 1996 with the broad scale deployment of insect growth regulators for whitefly control (the hard technologies), concomitant with development and deployment of key knowledge resources (e.g. new sampling plans, action thresholds and resistance management plans) and extensive collaboration and participatory education with the industry (the soft technologies) (Ellsworth *et al.*, 1996b; Ellsworth and Martinez-Carrillo, 2001; Naranjo and Ellsworth, 2009a, 2009b).

Figure 8.1 shows how to two key pests, *B. tabaci* (a whitefly) and *Lygus hesperus*, were managed while maintaining very low risks of pest resurgence and secondary pest outbreaks. Avoidance practices are further subdivided into three functional layers: Crop Management for plant health contains many key cultural controls; Exploitation of Pest Biology & Ecology leverages key knowledge resources and enables the key tactic of conservation biological control; Area-Wide Impact is the set of practices needed to provide shared benefits of IPM to all regionally, even to farmers of non-cotton crops impacted by these same polyphagous pests. There are many interactions among the IPM building blocks depicted, perhaps paramount among them the use of selective insecticides (hard technology) as an enabling agent for natural enemy conservation (soft technology), and the sharing and restrained use of chemistries (hard technology; resistance management) through active programmes, agreements, and voluntary compliance supported by cross-commodity agreements (soft technology).

This IPM system depended on a tight integration between the properly timed uses of selective insecticides and conservation biological control. These two elements in concert with other processes (e.g. weather factors) that contributed to the in-field mortality dynamics of whiteflies constituted an ecological process referred to as bio-residual (Ellsworth and Martinez-Carrillo, 2001). Bio-residual as a conceptual and cultural shift away from complete reliance on chemical residual for the control of insect pests was regularly taught and demonstrated to farmers at the time. Visible field experiments and demonstrations showed how the dynamics of bio-residual could be disabled through improper decision making and use of broad-spectrum insecticides (Fig. 9.1), leading to additional costs in primary and secondary target pest control. Despite large differentials in per acre per spray costs between these newer, selective insecticides and the older and 'cheaper' products, Cooperative Extension scientists were able to demonstrate the season-long savings and resilience of the new approach. Subscription to the new IPM plan of 1996 was very high and the system stabilized.

Throughout this history, practitioners and the scientific community could easily see the need for efficient management of whiteflies being necessary in all affected crops regionally. The regional sequence of spring melon production, summer cotton and autumn/winter melon and vegetable production in Arizona was ideally suited to the ecological requirements of whiteflies. After initial

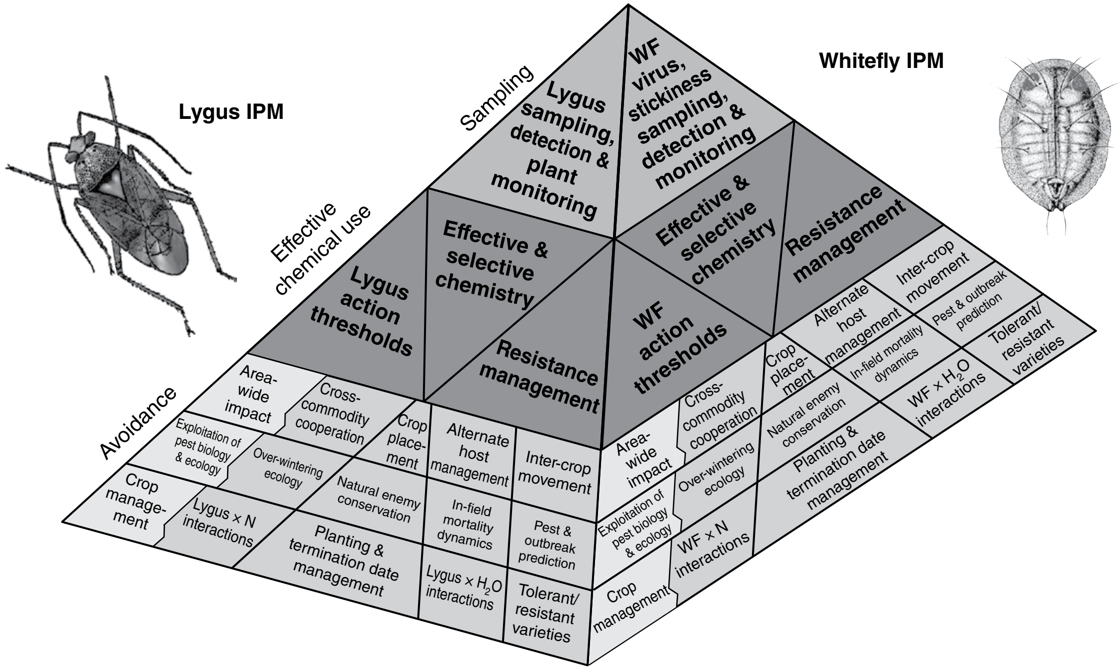

Fig. 9.1. The Arizona cotton IPM strategy fully integrates tactics (hard and soft technologies) of avoidance and prevention (foundation), and sampling (cap) and effective pesticide use (middle) to manage its two key pests, *B. tabaci* (a whitefly) and *Lygus hesperus*. (Adapted from Ellsworth and Martinez-Carrillo, 2001.)

landmark farmer agreements were established in 1999 for the 'sharing' of buprofezin, an insect growth regulator, as a key active ingredient across the agricultural landscape, Palumbo *et al.* (2003) then established formal cross-commodity agreements for the use of another class of insecticides, neonicotinoids, in the system. As a highly effective insecticidal control measure for whiteflies, susceptibility to neonicotinoids was a classic common pool resource that would require management in order to preserve product performance. These compounds were highly effective in vegetables and melons both as soil systemic treatments (especially the neonicotinoid imidacloprid) and as topical sprays (especially the neonicotinoid acetamiprid). Additionally, while these compounds were also effective in cotton, farmers voluntarily agreed to forgo the use of foliar neonicotinoids in cotton (mainly the neonicotinoid acetamiprid) in more complex agroecosystems where melons and/or vegetables were also grown using soil systemic treatments (the neonicotinoid imidacloprid). Therefore, despite the short-run economic benefits of everyone using neonicotinoids everywhere, farmers chose to limit their use to preserve insecticide susceptibility across the agroecosystem (Ellsworth *et al.*, 2010).

This cross-commodity cooperation, and indeed all of the progress in the whitefly IPM strategy, would not have been possible without regular, formal as well as informal, engagement inclusive of all affected stakeholders in a participatory research and Cooperative Extension process. And, core to this successful engagement is a trusting relationship with the developers and teachers of IPM, which was served well by the stakeholders' shared values of transparency. Despite the highly competitive and often proprietary nature of melon and vegetable production in Arizona, stakeholders had a 'common concern entry point' (*sensu* Sayer *et al.*, 2013) that led them to transparent negotiation, development and publication of neonicotinoid sharing guidelines (Palumbo *et al.*, 2003). What's important here is that this in itself was not a panacea for IPM of whiteflies or even for chemical control of whiteflies. But it was an important first step to building trust and cementing a culture where common pool resources like susceptibility to all whitefly insecticides could be more easily contemplated, addressed and implemented, even in the absence of formal agreements. In short, resistance management, as a key tactic of IPM (Fig. 9.1), is now discussed prior to the launch of each insecticide introduced to the Arizona cotton, melon and vegetable markets. Follow-up assessments of the 2003 cross-commodity guidelines a decade later showed that farmers were still voluntarily complying (Ellsworth *et al.*, 2013).

The Arizona whitefly plan (Ellsworth and Martinez-Carrillo, 2001) is a demonstration of the high degree of integration of both hard and soft technologies necessary to technically develop and deploy a successful IPM strategy. It would be a mistake to attribute the success only to the hard technologies developed and deployed. Selective whitefly chemical controls, seeds/varieties, plus water and nitrogen are ostensibly the hard technologies of this plan, just four of the building blocks (Fig. 9.1). The remaining 12 building blocks are the soft technologies that support IPM, from sampling plans and other technical requirements for successful chemical control to broad understanding and practice of natural enemy conservation and the aforementioned cross-commodity cooperation. Even still, whitefly management is merely a single facet of a multi-dimensional, multi-faceted IPM strategy for managing all insect and other pests.

The introduction of Bt cottons in 1996 was the shared cornerstone of the cotton IPM plan, 'tolerant/resistance varieties' (Fig. 9.1). The immunity conferred to cotton against pink bollworm was extraordinary and unfailingly 'high dose'. The first instars, subject to all sampling effort in the past, were perfectly able to still penetrate and gain entry to the boll interior. And, locally abundant moths still arrived in pheromone traps. Knowledge resources had to be put into place well before product launch (e.g. Ellsworth *et al.*, 1995a, 1995b, 1996a) to support the technology and to engender confidence in practitioners that these first instars were not going to survive in this new cotton. Otherwise, producers would have most certainly oversprayed their Bt cotton (as was becoming common practice for *H. zea* control in the mid-south US), eroding any benefit of investing in this new technology. Producers by and large did not spray, except in their non-Bt plantings, and this removal of broad-spectrum pyrethroids and organophosphates formally used to control pink bollworm moth flights helped to support the newly developing cotton habitat for natural enemies.

Key selective technologies and two facets of the IPM structure in place for pink bollworm and whitefly starting in 1996 left only *Lygus* bugs (*Lygus hesperus*) as the remaining key cotton insect pest to address. While IPM advances were made in establishment of action thresholds and decision making systems, *Lygus* control largely depended on the use of an organophosphate (acephate), a carbamate (oxamyl) or a cyclodiene (endosulfan), each of which risked undermining goals of conservation biological control (Naranjo *et al.*, 2004). With the discovery of *Lygus* efficacy with flonicamid, formerly only in worldwide development for aphid control, the Arizona system had access to a control agent that was safe to the beneficials of the system starting in 2006. Importantly, due to the stability and resilience that was progressively built into the IPM system for pink bollworm and whitefly management, heteropteran opportunist pests did not fill the void left when sprays diminished for the control of the other two key pests. This is a stark contrast to the large increase in hemipteran pests in the Chinese cotton system (Wang *et al.*, 2009; Lu *et al.*, 2010).

In the past, Arizona cotton farmers were spraying on average 10–13 times per season with broad spectrum insecticides, they now spray just twice with narrow spectrum insecticides that are safe for generalist predators and therefore compatible with goals in conservation biological control (Naranjo and Ellsworth, 2009b; Anderson *et al.*, 2019). In addition, there has been over 90% reduction in broad-spectrum insecticide use in Arizona cotton since 1996, and cumulatively, more than 25 million lb of active ingredient that have been eliminated from the system (Ellsworth *et al.*, 2018). Cumulatively this has saved cotton farmers in this state more than $500 million or about $274/ha/year.

While it would be seductively simple to attribute entirely these advances to the cascade of major hard technological products that were developed over this period, this would ignore the importance of the soft technological advances and cultural context in which IPM was locally derived, developed and deployed. Of the $274/ha in annual savings, fully 42% ($117/ha) is attributed to gains in conservation biological control (Ellsworth *et al.*, 2018), which aligns well with Arizona pest managers' own estimates of the value of biological control in Arizona cotton ($108/ha; Naranjo *et al.*, 2015).

The Future of IPM

IPM will continue to evolve in tandem with pests that evolve to different environmental conditions and pest management. This evolution of IPM will be aided through the development of new hard technological advances. However, as we have demonstrated in this chapter, soft technologies must be developed to complement these hard technologies to advance IPM. Perhaps the recent focus on interdisciplinary efforts will spur this forward. Regardless, despite the advances in both hard and soft technologies, the framework laid out by Stern *et al.* (1959) continues to be relevant now and for the foreseeable future.

Concentrated external influences

Agriculture in the US is becoming increasingly sophisticated and specialized and will continue to do so as fewer people farm. In addition, the number of companies that provide products and both hard and soft technologies to these farmers will continue to decrease. While, at some point, the market may become so concentrated that farmers lose money from a lack of a fair competitive market, past evaluations suggest that farmers have economically benefited from the aggregation of companies (National Research Council, 2010). However, in the future, the ability of a single individual farmer to efficiently manage all the decisions on the farm will be challenged. While more electronic data are collected and this is processed more efficiently over time, new complications arise. For example, while many farmers are excellent at troubleshooting mechanical problems, few farmers are skilled at troubleshooting problems related to information technology. As in other sectors of the economy, individuals or corporations that can provide products and information to help navigate this complexity will continue to be more valuable. Therefore, the influence of the agrochemical and seed industry, as well as trusted Cooperative Extension scientists, will continue to grow in importance, as well as private consulting. These entities will be able to provide tailored information as soft technology to guide farmers in their decision making processes.

Site-specific management

Intertwined with the increasing importance of external influences, has been the tendency to move in-season pest management inputs to at-planting (seed treatments and crop traits, for example). However, with the increasing ability to provide tailored information to farmers, it may be possible to provide traits or pesticides that are only 'activated' when needed. This may be driven by the increasing use of digital data and the advent of artificial intelligence. While data are plentiful now, it has been difficult to provide farmers with useful information from these data to make informed pest management decisions. This may also be driven by the trend of governments to restrict broad-spectrum insecticides. If the agricultural industry can limit the use of these products to where they are needed using a combination of digital data and traits or pesticides that are activated only when needed, where they are needed, it may be possible to maintain the use of many products in an IPM system.

Additionally, most current pest management decisions are made on the farm or field level. However, farmers are increasingly adopting planters, nitrogen applicators and sprayers that can be site-specifically adjusted. To recover the full value of these investments, pest management decisions will no longer be made on a field-to-field basis, but will vary within individual fields.

Increased ability to predict pest problems

Ecoinformatics has been defined as ecological studies that use pre-existing datasets. Recent advances in the application of big data methods in ecology have significantly improved the ability to make predictions in this field (Rosenheim and Gratton, 2017). As computing power and data collection continue to expand, predictive power should increase as well. If pest problems can then be anticipated in a given set of circumstances, IPM efforts may become more proactive rather than reactive. This is not unique to IPM or agriculture, as nearly every area, from business to political science, seeks to harness massive datasets for predictive power. One inefficiency identified from medicine is the lack of willingness to share data across healthcare systems (Kannampallil *et al.*, 2104). While this could be a potential problem for agriculture, given the industry consolidation, in the future, there could be a few large companies who efficiently collect and use data across most of the US agricultural landscape.

Conclusions

Recently, Peterson *et al.* (2018) asked 'whatever happened to IPM?' and encouraged those working in agriculture to re-evaluate what it means to be successful in modern pest management. Others have, justifiably, criticized economic thresholds, pointing out that many are based on outdated information or unpublished data, are unreliable, and rely on the use of impractical scouting methods and have argued for more research into these areas (Leather and Atanasova, 2017; Ramsden *et al.*, 2017). While we agree with these criticisms (see our example of *O. melanopus* and wheat), we also argue that more emphasis must be placed on the soft technologies for IPM, which incorporates not only standard transactional economics, but also the social sciences considered by behavioural economists (Chapter 1). As demonstrated by our examples, the ultimate success of IPM relies on a multi-pronged approach. Farmers should not expect to have pest-free row crops, and consumers should be willing to tolerate some insect activity. Moreover, farmers must be willing to adapt to changing pest behaviour and market values.

We also wish to highlight an earlier point about US Cooperative Extension. If the reader accepts the conclusions of this chapter, then Cooperative Extension is important in the development and execution of the soft technologies that enhance IPM. Therefore, the structure of Cooperative Extension is also likely important to the success of IPM. We earlier pointed out the desire of farmers to minimize economic risk and the desire for companies to achieve a return on investment for their development of hard technologies. In contrast, the goals of those in Cooperative Extension are dependent on the particular structure of the system, which can vary on the state, university, department, region and county level. For example, some states refer to university faculty with extension appointments as 'specialists'. Appointments refer to the amount of funding provided from the extension budget versus the teaching or research budget. Logically, specialists should be rewarded based on their performance for each appointment. For example, if a specialist has a 70% extension appointment and 30% research appointment, then rewards for performance should reflect achievements based on these efforts. However, some universities prioritize research efforts, since they are easily quantifiable (number of peer-reviewed publications, total impact factor of peer-reviewed publications, number and total funds generated from grants) and because they enhance university reputation (publications) and funding (grants). In contrast, extension efforts of Cooperative Extension specialists are often not as easily quantified and are, in some cases, minimized relative to research efforts. While research efforts often provide knowledge to support IPM, the focus of these efforts may not necessarily be oriented toward the development of soft technologies to complement IPM. In contrast, extension efforts are focused on stakeholder needs and priorities and, in the case of pest management, are potentially a better fit into the IPM framework. Therefore, we posit that the structure of the Cooperative Extension framework is an important component to the success of IPM systems.

Part of what makes wicked problems so horrific is that every wicked problem is unique. Furthermore, the case study approach does not always generalize to a solution that works elsewhere. IPM as a dynamic strategy to confront pest problems and maintain stakeholder goals for economic risk reduction should be translatable to new and different environments. For example, the Arizona cotton IPM system (Ellsworth and Martinez-Carrillo, 2001; Ellsworth *et al.*, 2006; Naranjo and Ellsworth, 2009b) was extended to nearby northern Mexico where IPM was not functioning despite access to the hard technology that helped Arizona to be successful. What was missing was the change agent, Cooperative Extension, and the soft technologies, translational research and demonstration, and educational support to adopting stakeholders needed for IPM to be successful (Anderson *et al.*, 2019). After an intensive, 17-month extension campaign in Mexico by Arizona workers, farmers adopted the Arizona cotton IPM strategy for whitefly and *Lygus* management that resulted, in 2012, in a 31–40% decrease in sprays, 34% reduction in insecticide costs and a 23–86% reduction in the use of broad-spectrum insecticides, for a single-year saving of over $1.6 million (Anderson *et al.*, 2019).

Part of the uniqueness of this system is the inherent design, including geographical and societal characteristics. Arizona cotton is grown by relatively few farmers, compared with many other farming areas of the US, and relies on irrigation in valleys separated by arid areas with few hosts that can harbour cotton pests. Furthermore, this region is serviced by a high-quality professional pest control advisor industry, maintained through state-licensed and mandated educational requirements and continuing education, which provides pest control advice to clients for a fee. Arguably, this makes implementing soft technologies easier, since there are fewer farmers to reach and since hard technologies can be implemented relatively uniformly and rapidly. Similar success can be found in the Australian cotton system, which has many of the same characteristics, and where Bt crop resistance management has been very successful (Downes *et al.*, 2017). In Arizona, too, there might be greater incentives for farmers to be technologically adroit because of their very high yields (with concomitant high values and high costs of inputs) and year-round growing conditions that favour pest development. These systems contrast with areas of the US like the Midwest, where vast areas are farmed by many individuals, and the south-eastern US, where alternative crop and non-crop hosts are often available for many pest species. Moreover, professional pest control advisors do not consult in all regions or in all crops. In these geographies and social situations, creating and implementing effective technologies may be even more challenging. Despite these challenges, the successful implementation of soft technologies in these systems should not be downplayed. Rather, we highlighted the Arizona cotton system to model a successful framework that can inspire other systems. This example demonstrates the power of soft technology to tame a disrupted system with multiple hard technologies and crops (a formerly wicked problem).

Wicked problems defy broad-scale resolution because solutions are specific in time and place and are therefore ‘one-offs’. It is frustrating to consider pest control, the subject of IPM, as wicked problems. However, IPM should be designed to minimize stakeholder risks to the economy, environment and society, and IPM must be integrated, operational on a scale respectful of the ecosystem in which it is embedded, and progressively localized and adapted to the site and users involved. As re-imagined, IPM is the perfect foil for the wicked problems posed by pests competing with humans for a share of this planet. The key to the development of successful IPM strategies is to avoid seeking or relying on only the hard technical ‘solution’, but rather to invest heavily in the array of supporting soft technologies and all the transdisciplinary needs of the system and the stakeholders. Inclusive engagement, transparency, participatory learning and trust in all aspects of stakeholder interactions are the enabling features of a strategic IPM solution that is both adaptively, progressively managed and resilient to the inevitable perturbations of the system.

In conclusion, we do not want to downplay the role of hard technologies to bolster IPM. Rather we wish to highlight the underappreciated role that soft technologies play in complementing these hard technologies. Our various examples of IPM complications were similar in that the development or implementation of appropriate soft technologies to complement hard technologies was absent. Farmers that are on the front end of innovation tend to be the quickest adopters of hard technologies (Rogers, 2003). However, the speedy adoption of hard technology can quickly be followed by failure if, for example, resistance to the technology develops. University Cooperative Extension has a unique role to play in the development of soft technologies, since most hard technologies are developed by large companies that are required by stakeholders to generate the maximum profit for their particular technology. Cooperative Extension can bridge the gap between farmers and companies providing these technologies by creating soft technologies that benefit all parties, while minimizing environmental impacts. While IPM is still developing in the US, we see current examples and future developments that are encouraging for positive impacts on IPM as a whole.

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10

Perseverance Pays Off: Finishing the Integrated Pest Management Marathon with Economics

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The good news is that classical biological control, augmentative biological control, host-plant resistance for field crops and the use of economic thresholds are often economical solutions to problems in pest management (Naranjo *et al.*, Chapter 4; Onstad, Chapter 5; Onstad *et al.*, Chapter 7). Successful classical biological control and host-plant resistance supported by government research and development programmes likely produce benefits that not only justify their deployment but also cover any losses due to research failures (Naranjo *et al.*, Chapter 4; Onstad, Chapter 5). The value of mosquito control for public health improvement and nuisance reduction can also be demonstrated with economics (Halasa-Rappel and Shepard, Chapter 2).

The value of more extensive, more integrated, and more ambitious integrated pest management (IPM) programmes depends on the situation. Rejesus (Chapter 3) concluded that the many varied attempts to improve IPM through soft technology and Farmer Field Schools did reduce pesticide use but often failed to increase farmer profits and crop yields. Norton *et al.* (Chapter 8) demonstrated positive impacts of large-scale IPM programmes, but agreed with Rejesus that many economic analyses may be biased in the way they collect data. Reisig *et al.* (Chapter 9) highlighted the economic success of the IPM programme for melon and cotton pests in the US state of Arizona. In general, simultaneous management of multiple pests on a single crop or a single pest on multiple crops in the same area remains the ultimate challenge for entomologists in many parts of the world. As Reisig *et al.* (Chapter 9) stated, real solutions must consider the interdisciplinary needs of stakeholders.

In this chapter, we attempt to combine final philosophical thoughts with practical suggestions for future work. First, we provide an overview of IPM strategy. We emphasize the value of integrating design and control tactics to provide a solid foundation for IPM. Second, we focus some attention on how funding, or lack of funding, may have influenced the historical paucity of economic analyses. Third, we provide some thoughts on education and Cooperative Extension and outreach to farmers from an economics perspective. Fourth, we look at future innovations within IPM. We conclude the chapter with encouragement to readers to add economic analysis as a tool to help facilitate scientific decision making.

Strategies for Integrated Pest Management

When a stakeholder makes a long-term (>2 years) plan for managing pests, she is developing a strategy that combines decisions about design and choices about control tactics. The strategy could include any crop rotation schedule, planting scheme, tillage style, plan to use sampling and an economic threshold, habitat modification for biological control or anything else. Each deployment of a design element or a control tactic consists of (i) a product, defined as a chemical or biological insecticidal active, species, or material, and (ii) information and

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procedures that make the wise and rational deployment possible (Onstad, Chapter 5; Onstad *et al.*, Chapter 7). The product, species or material such as a seed, a chemical or a natural enemy may have the potential to bring a higher profit or a lower risk of loss to the stakeholder. However, without the information and procedures based on knowledge of the pest's population dynamics, genetics and behaviour, the potential of the hard technology (Reisig *et al.*, Chapter 9) will rarely be realized. In addition, knowledge of the specific environment and any interactions among the hard technologies (products, materials, livestock) will also be needed. These procedures and information are the soft technologies described by Reisig *et al.* (Chapter 9). They can be provided by teachers, Cooperative Extension, Farmer Field Schools, crop consultants and the sellers of hard technology (Rejesus, Chapter 2; Reisig *et al.*, Chapter 9).

Note that these procedures, information collection, research and soft technologies should never be considered free. Yes, a farmer may not pay directly for research, but society or industry does (Brown *et al.*, Chapter 6). Most importantly, sampling to collect information about pests, natural enemies and the environment costs someone, usually the farmer, time and money (Onstad *et al.*, Chapter 7). To make insect management cost effective, the IPM goals, the necessary information and the acceptable precision must always be kept in mind (Brown *et al.*, Chapter 6; Onstad *et al.*, Chapter 7).

Area-wide pest management increases the need for procedures, information and soft technologies (Halasa-Rappel and Shepard, Chapter 2). This is true whether we think of strategy development or seasonal use of tactics. Coordination of farmer behaviours or activities of public health agencies and citizens in a city requires more information and more analysis. Genetic pest management (Brown *et al.*, Chapter 6), classical biological control (Naranjo *et al.*, Chapter 4) and insect resistance management (Onstad, 2014), particularly for highly effective, and therefore widely adopted, host-plant resistance (Onstad, Chapter 5), are all examples of area-wide pest management.

An example of area-wide pest management is the effort to keep a region of Australia free of the Queensland fruit fly, *Bactrocera tryoni*, one of the most significant economic pests of horticultural goods in Australia (Dominiak, 2019). It is endemic to Australia and is a key target for trade partners who import horticultural goods from Australia leading to the Code of Practice for the Management of Queensland fruit fly (Dominiak *et al.*, 2015, Standing Committee on Agriculture and Resource Management, 1996). Due to the potential damage that could occur upon the spread of this pest, the Sunraysia area of Australia (north-western Victoria and south-western New South Wales) has designated pest-free areas and exclusion zones, from which growers have more access to export and domestic markets relative to areas where the pest is endemic. In the pest-free area, eradication of Queensland fruit fly outbreaks as well as post-harvest treatments are required (Florec *et al.*, 2013). Florec *et al.* (2013) examined the economics of area-wide pest management against this pest. The control budget was approximately A$7 million per year, of which 85% is allocated to surveillance, eradication and roadblocks. In the analysis, it was found that reducing the probability of outbreaks by enforcing stricter control at roadblock sites, thus reducing post-harvest disinfection insecticide treatments, was more economical compared with better surveillance or faster eradication. Post-harvest disinfection costs, which can vary in the quantity of produce treated and the cost per treatment, are expensive and are done when there is need to control Queensland fruit fly infestations. Benefits derived from reducing the probability of Queensland fruit fly infestation were sensitive to post-harvest disinfection costs. Florec *et al.* (2013) concluded that improving the ability to identify, quantify and separate produce needing these treatments by geographical area is an important consideration.

Note that, according to Brown *et al.* (Chapter 6), area-wide pest management is complicated by the multiple levels of decisions and decision makers. The regional project coordinator makes decisions about area-wide deployment of pest management, and individuals then adapt their pest management efforts based on how effective area-wide management is. Kovacs *et al.* (2014) examined the economics of controlling emerald ash borer (*Agrilus planipennis*) in an urban forest and determined that aggregating budget across municipal districts would lead to a more robust control strategy as opposed to singular efforts from each municipality. In this case, emerald ash borer has strong dispersal and population growth capabilities, meaning that management executed at a municipal level would likely have little effect. Only by combining locally connected municipalities into a coordinated area-wide consortium, could the benefits of IPM strategies be increased. It is not always easy to predict how individuals affected by area-wide pest management will behave. Sometimes engineers have predicted a given impact from a new technology, but did not anticipate the (rational) behavioural responses to that technology (e.g. driving more with a more efficient vehicle even though reduced energy use was the goal). Note that greater area-wide management might decrease incentives for individual management efforts (Brown *et al.*, Chapter 6).

This diversity of perspectives and behaviours for two stakeholders exemplifies the point that each economic analysis must clearly identify both the stakeholder and the purpose of the IPM and analysis (Onstad and Crain, Chapter 1). Halasa and Shepard (Chapter 2) take the perspective of the local mosquito control district, a social perspective and investigate economics over a single year. Naranjo *et al.* (Chapter 4) and Brown *et al.* (Chapter 6) take the perspective of a government agency or central decision maker and consider long-term economics. Rejesus (Chapter 3) considers value for an average farmer involved in Farmer Field Schools over a year or two. Onstad *et al.* (Chapter 7) take the perspective of a farmer that wants to be efficient over a growing season. The other chapters consider a variety of stakeholders, perspectives and goals.

We propose that the best approach to integration of tactics is to first attempt to combine a design tactic with a control tactic targeting the same pest. Reisig *et al.* (Chapter 9) describe the highly successful integration of host plant resistance (design) with sterile insect release (control) and mating disruption (control) in the eradication of *Pectinophora gossypiella* in south-western US cotton (*Gossypium hirsutum*). Alyokhin *et al.* (2015) performed a very good analysis of agricultural landscape design and its influence on management of *Leptinotarsa decemlineata* in potato (*Solanum tuberosum*) fields across the US. Management was easier or more sustainable when the landscapes had common natural enemies, alternative host plants and volunteer potato plants acting as refuge, and typical schedules of crop rotation (all design elements) that were integrated with chemical insecticide use. Norton *et al.* (1983) modelled the economics of integrating cattle resistance (design), acaricide control of ticks, cattle stocking rates (control) and scheduling of paddock use (design). Brown *et al.* (Chapter 6) discussed the integration of release of genetically modified pests (control) with host-plant resistance (design) to delay the evolution of resistance to the design or to both. Marasas *et al.* (1999) evaluated the economics of IPM for *Diuraphis noxia* on wheat (*Triticum aestivum*) in South Africa. The programme comprised resistance breeding (design), chemical insecticides (control) and biological control. The returns to the research investment for the period 1993–2000 were estimated in a cost–benefit analysis with an economic surplus approach. The rate of return for the public investment was well over 34% for all scenarios considered. It is also possible that combining two different design tactics, such as host-plant resistance and scheduling of crop rotation (Onstad *et al.*, 2003; Crowder *et al.*, 2005), could also be superior to combining two types of control tactics.

Funding for IPM Research and Economics

Reisig *et al.* (Chapter 9) and Naranjo *et al.* (Chapter 4) indicate that funding for IPM research and development should be increased. We believe that economics can both show the past value of IPM as well as the potential value of future investments.

According to Onstad and Knolhoff (2009) and our own, more recent survey (Chapter 1), only 1% of the entomological articles published since 1972 have included an economic analysis of insect pest management. This percentage is similar to that found by Naranjo *et al.* (Chapter 4) for all classical biological control projects. From 1972–2006 in the *Journal of Economic Entomology*, one economic evaluation was published every 2–3 years on average for each of five field crops and for cattle (Onstad and Knolhoff, 2009). Farmers growing these crops and raising cattle can tell us if they were satisfied with progress in IPM for their problems. Citizens can tell us if they were satisfied with the progress in reducing social and environmental impacts of IPM.

Much of the research surveyed by Onstad and Knolhoff (2009) was done without special, external funds; for those supported by external sources in the US, state agencies were a common source of funds. The analysis of funding sources by Onstad and Knolhoff (2009) clearly indicated that the United States Department of Agriculture (USDA) competitive research grant programmes can play a larger role in supporting economic evaluations in economic entomology. All USDA funded projects are expected to describe the impacts of the research for society. Grants awarded to entomologists by the

USDA competitive grants programme played an increasing role over time and supported about 20% of the research projects with economic evaluations during 2000–2006. However, Onstad and Knolhoff (2009) also determined that of 79 USDA-supported, arthropod management projects funded from 2000 to 2006, only eight projects published economic evaluations by 2007 (Onstad and Knolhoff, 2009).

Education, Cooperative Extension and Farmer Field Schools

In the US, university administration can influence faculty behaviour and interest in the economics of IPM. First, there has been an obvious emphasis on efforts to acquire external funds for research. Thus, there is a vicious circle of funding agencies not emphasizing economics and university entomologists following the money. Then, successful entomologists review new proposals that do not focus on economics and declare that they are excellent. Second, but more obvious, universities control the education of future economic entomologists. Because universities hire researchers who succeed in obtaining grants that de-emphasize economics, it is natural for these scientists to teach what they know and what has made them successful, not economic evaluations.

Napit *et al.* (1988) evaluated the economic benefits of Cooperative Extension IPM programmes in more than 10 states in the US and for multiple commodities. They found that net returns per ha increased for farmers adopting more IPM. However, they discovered that pesticide use often increased with IPM adoption. Goetz and Davlasheridze (2017) used annual data from 1983 to 2010 covering all states to examine the impact of all Extension programmes in the US on net changes in the number of farmers. They concluded that without Extension, up to 28% additional farmers would have stopped farming. Overall, they believed that extension programmes are a cost-effective way of keeping farmers in agriculture. For example, Goetz and Davlasheridze (2017) suggested that one reason why Cooperative Extension is so effective is that farmers share insights they learn from Extension with other farmers, thus highly leveraging the value of each dollar spent on such programming, which is the same approach taken by IPM Farmer Field Schools in developing countries.

Rejesus (Chapter 3) concluded that pesticide use may decline but profits and harvested crop yields may not increase when farmers participate in IPM-focused Farmer Field Schools. This conclusion became apparent when an unbiased evaluation was made, similar to the approach by Feder *et al.* (2004). Feder *et al.* (2004) concluded that the IPM Farmer Field Schools in Indonesia did not improve the environmental or economic conditions for the participants. Sanglestsawai *et al.* (2015) concluded that both the amount of labour employed and profits were not statistically different between participants and non-participants in Farmer Field Schools. These studies draw attention to the way the participants are taught and how the information is disseminated in their communities. An alternative concern could be that the IPM tactics being taught do not account for the complexities, differences and difficulties experienced by all the farmers in the community. It would be interesting to know how the original sponsors and supporters of these Farmer Field Schools now feel about their investments. Longer-term studies could also be used to determine if participants, who did reduce their insecticide use in the few years after participation, return to other habits and labour-saving activities that may involve greater insecticide use.

It is worth considering that farmer yields are impacted by more than just insect pests. We have emphasized the details of managing insect pests, but agricultural systems are also susceptible to weeds, bacterial/fungal/viral diseases, and nutrient and water deficiencies that also decrease yields. Measuring the economic benefits to insect management are important but understanding the global constraints on a farmer's yield potential, and how they interact, are also vital to continued success (see Pinnschmidt *et al.*, 1997 and Lobell *et al.*, 2009).

Innovation and Technology

It is an exciting time to be in IPM. Despite the numerous challenges highlighted by authors throughout this book, we stand in a period of rapid technological advance that affords us with an unparalleled source of opportunity. Some authors in this book have argued for more work and more innovations with regard to soft technologies, procedures, outreach and education. Others have also argued that we need more products, materials and identified species (hard technologies) to continue the successes of biological control and host-plant resistance. Genetic pest management (Brown *et al.*, Chapter 6) certainly has been and will continue to be considered innovative with regard to hard technology (i.e. development of insect genotypes). We believe that innovation in all areas of research and development will always be necessary to maintain, if not improve, our ability to manage invasive species, resistant species, and the species that continue to cause public health agencies and farmers problems.

Stakeholders hope that technological advancements will make pest management faster, cheaper, or more reliable. Economics can help determine the value of technology, which can be difficult to measure. For example, in area-wide management of mosquitoes (Chapter 2), we can measure the willingness to pay for intervention. Similarly, economic analyses can help identify when IPM systems should consider changes in design or control. Gallardo and Wang (2013) determined that apple and pear growers in the US Pacific Northwest would pay approximately $26/acre and $36/acre, respectively, to decrease the probability of pesticide toxicity to natural enemies. For technology developers, this is an indicator that a solution, facilitating either a change in design or control, which could meet the grower's goal (of reducing the probability of pesticide toxicity against natural enemies) would be desirable, at the right price.

Often modern technology is judged by its convenience for farmers in a way that implies that convenience and time/labour-saving is a factor separate from other management aspects. For example, insecticidal seed is often considered more convenient than an application of an insecticide. Which leads to the thought that changes in design that reduce the need for seasonal control are likely to be considered more convenient, unless the design requires maintenance that increases the demand for labour. But the main point for this book is that economic analyses can easily account for cost of labour or a farmer's willingness to pay for an hour or two of free time. This makes convenience just one of the factors in the overall economic evaluation.

A significant challenge highlighted earlier is the paucity of economic analysis in many systems. An exciting new area for agriculture is the deployment of farm management systems, which can provide a cost tracking service for grower operations. However, the same data types needed to understand the costs in agronomic systems (e.g. field boundaries and crop protection chemistry spraying area and date) can be leveraged to understand the benefits. Farm management systems may provide the opportunity to collect cost and yield data over both time and space while also collecting valuable metadata. When metadata is complete for a specific question, each field using a farm management system can become an experimental unit, which could contribute to powerful analytical techniques (Willers *et al.*, 2008). Designing IPM systems could become simpler by leveraging large amounts of site-specific experiments across similar geographies against similar pests.

A system that holds all the information needed to make an economic analysis is important but can only provide reliable results if the underlying data quality is high. Many researchers are starting to study new sensors that may afford IPM practitioners better data-collection tools with less opportunity for human bias or logistical concern. For example, in the past, mark, release, recapture experiments were the norm for researchers hoping to understand insect dispersal (Russell *et al.*, 2005). Now, new technologies, or new deployment of old technologies, are providing entomologists with opportunities to gather more robust data than ever before. For example, vertical-looking radar has been used to monitor long-range insect migration by observing flights over a network of fixed-location units, and harmonic radar is improving, making it possible to attach tags to individual insects and monitor dispersal behaviour (Chapman *et al.*, 2011). Insect traps are also becoming more sophisticated. Several companies now offer products that use automated pest counting technology ranging from image capture and detection (Ding and Taylor, 2016) to wingbeat sensors (Chen *et al.*, 2014). These technologies will have an opportunity to change insect pest detection and improve the decisions made from this information.

Furthermore, the data and technology discussed here, if implemented in a farm management system or associated with the correct metadata, will offer IPM practitioners the ability to more easily validate IPM systems. By tracking farmer decisions from varieties planted and planting date to crop protection chemical applications and measuring yield, all factors that influence the success of IPM can be evaluated for impact in site-specific experiments.

Technology and data can particularly help in situations where sampling for insects is challenging. As highlighted by Onstad *et al.* (Chapter 7), the sampling of insects is a challenging scientific endeavour balancing the costs associated with sampling, the ability to detect economic damage levels and the costs associated with treating insect pests as appropriate. Adam *et al.* (2012) evaluated the economics of IPM decisions for several grain storage locations in the US where lesser grain borer, *Rhyzopertha dominica*, can damage and infest stored wheat. Their analysis found that doing nothing in the face of lesser grain borer infestation was the costliest strategy with an associated loss of US$0.12 per bushel of wheat. The optimal strategy depended on the amount of grain bins that needed to be fumigated. If all bins needed fumigation, then a sampling strategy simply added to the cost; fumigation of all bins cost approximately $0.033/bu compared with a cost of $0.044/bu when sampling accompanied the fumigation of all bins (sampling cost is $0.011/bu). When 60% of bins required fumigation, the costs of a calendar-applied fumigation was similar to the sampling and fumigation strategy. For anything below 60% of bins requiring fumigations, the optimal strategy was to sample and treat. Adam *et al.* (2012) claim that, in this system, investments that lower fumigation costs (closed loop fumigation systems) and implement aeration systems may provide better return on investment because sampling was so challenging. In this example, sensors that could detect and monitor insects better stand to significantly help stored grain IPM practitioners make more economical decisions. It is another opportunity to consider system design (opportunity for technology) when control elements do not allow a stakeholder to meet all her desirable goals.

Big data will become a key challenge for future IPM practitioners in the same way big data derived from DNA and RNA sequencing technologies presented challenges to molecular biology researchers. A new technology, capable of producing large amounts of data quickly, was now available, but how to use that technology and data was not well understood. With improvements to global positioning systems, internet-of-things networks provided by wireless internet and cellular data networks, and imaging technology, just to name a few, researchers can collect much more data on insects than ever before. Wolfert *et al.* (2017) provide a review on big data in smart farming, and highlight some of the opportunities, challenges and key points for the future. They also highlight the important roles of many stakeholders in big data collection and analytics including traditional agricultural companies as well as new sources such as IBM, Google and the many technology-based start-ups.

To successfully manage arthropod pests, society needs all the innovations that science and industry can develop. We are concerned that a general focus on IPM failures by academia could limit society's willingness to invest in risky research and development. For example, Alyokhin *et al.* (2015, p. 343) declared that 'In the absence of IPM, excessive reliance on pesticides has led to repeated control failures due to evolution of resistance'. And Reisig *et al.* (Chapter 9) emphasized that overdependence on chemical insecticides usually leads to failure due to evolution of resistance. Both statements are true, but the focus on the ultimate failure seems to disregard any positive value of the insecticides while they were effective. Certainly, entomologists should be pessimistic about durability of any highly effective technology (Onstad, 2014). However, is the rate of failure for insecticides significantly different from that experienced for classical biological control? Naranjo *et al.* (Chapter 4) concluded that ~620 cases of classical biological control have been successful (the 10% success rate of Cock *et al.*, 2016), and ~5538 have been failures. We believe that society must be willing to take the risks and invest the money in IPM technology that likely will fail more than 50% of the time before we obtain a positive return on the investment no matter what kind of tactic is being explored. Of course, we can always use more wisdom when we implement innovative hard or soft technology. Economic analyses can help guide decision making and investment.

Conclusions

This book supports the fundamental paradigm for pest management that has existed for more than 50 years. However, we avoided defining integrated pest management in the first chapter for several reasons. We did not want to delay the focus on economics by being too philosophical. We also did not want to declare which and whose definition was the best. Most definitions of IPM express important but vague concerns for economics, environmental protection and social issues. The paradigm inspires us to improve pest management through integration of several types of tactics, but it gives us no specific guidance.

The IPM paradigm has reassured us with dogma that multiple tactics are best for managing pests. Yet how many of us have learned, and are happy to know, that a single tactic not related to insecticides, is fine. Think of American rootstock and phylloxera, or crop rotation and *Diabrotica* corn rootworms, or *Vedalia* beetle regulating the cottony-cushion scale. We don't even consider the economics because the successes are so obvious. These are all changes in design. And there is typically no concern for resistance evolution. Yet examples of the two *Diabrotica* species evolving resistance to crop rotation and Onstad's (2014) summary of the large number of cases of resistance to a variety of non-insecticidal tactics demonstrate that pests will likely evolve resistance whenever we rely on a single tactic that is very effective. However, this point is less important than the idea that we all have our biases, that we prefer some tactics over others, that we believe prophylactic chemical control is bad and we do not take the necessary step to counteract these biases. That step is an economic evaluation.

We propose that the first step in satisfying the three objectives of IPM must be a satisfactory economic analysis, because this is so much more feasible than determining how to reduce harm to the environment while feeding citizens and solving other social problems. We are aware that many entomologists wish to reduce chemical insecticide use as much as possible and make this their top priority. For most situations, we believe that reduction in insecticide use can truly be accomplished over the long run only with the support of an economic analysis. By an economic analysis, we do not mean only studies of farmer profit. We mean take the perspective of several stakeholders, perform the calculations, draw careful conclusions.

The main reason we use economics is to help make a good, if not the best, decision about managing insect pests. Nevertheless, economic analysis also provides one other valuable contribution to IPM: by measuring, recording and comparing monetary values, economics forces researchers and developers to rigorously account for the important factors. In essence, the best economic analyses provide the users with a systems perspective, similar to what a mathematical, biological model can do. If the monetary numbers seem wrong, we must either confront our assumptions about the components and behaviours within the pest system or challenge our expectations about this given IPM problem. If our assumptions are wrong, we may need to measure additional processes or record data under more environmental conditions and then reanalyse the economics. If the original economic analysis was correct and our expectations were wrong, then we realize that economics and rigorous analyses can protect us from blindly following dogma and past experience. (We are aware that economic analyses can also be influenced by biases.)

The results of economic analyses can help us determine not only what is, but also what could be. The economic evaluation can identify which factors in the IPM system are most important in their impact on the comparison of costs and benefits. After identification, one can decide how and where to affect change in the system. From society's perspective, should more subsidies be made, more funds be invested, or taxes levied to change behaviours? Should more money and effort be allocated to redesigning the system or to adjusting controls?

Ultimately, the question seems to be: are we attempting to solve problems or just make the pest system meet our expectations? The former rigorously takes the perspective of various stakeholders. The latter focuses on an entomologist's personal approach to and concern for the environment, the farmer or the citizens harmed by a mosquito. As stated above, economics should prevent entomologists from relying on their own perspectives about value and risk.

We all need the information about economics of IPM to participate fully and effectively in discussions and debates about funding and other support for IPM. All stakeholders will benefit from understanding the truth about the economics of their systems, even if we cannot tell the entire story in 2019. Thus, we believe that entomologists can form the teams and perform the analyses that will demonstrate, more than ever before, that IPM and the contributions of entomology are valuable to society.

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