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Issues

Social Ecological System Tools for Improving Crop Pest Management

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Abstract

Integrated pest management (IPM) is a valuable tool for reducing pesticide use and for pesticide resistance management. Despite the success of IPM over the last 50 yr, significant challenges remain to improving IPM delivery and adoption. We believe that insights can be obtained from the field of Social Ecological Systems (SES). We first describe the complexity of crop pest management and how various social actors influence grower decision making, including adoption of IPM. Second, we discuss how crop pest management fits the definition of an SES, including such factors as scale, dynamic complexities, critical resources, and important social–ecological interactions. Third, we describe heuristics and simulation models as tools to understand complex SES and develop new strategies. Finally, we conclude with a brief discussion of how social processes and SES techniques could improve crop pest management in the future, including the delivery of IPM, while reducing negative social and environmental impacts.

Key words: pesticides, risk, IPM, sustainability, resilience

Integrated pest management (IPM) is a decision support system for the selection and use of pest control tactics, singly or harmoniously coordinated into a management strategy, based on cost–benefit analyses that takes into account the interests of and impacts on producers, society, and the environment (Kogan 1998). Methods used in IPM can reduce pesticide use and conserve pesticide efficacy (Kogan 1998, Epstein and Zhang 2014). IPM programs have been estimated to have saved $1.3 billion in pesticide costs for almonds, cotton, oranges, and processing tomatoes since 1970 (Mullen et al. 2005). Examples of IPM tactics that may reduce either pest pressure or pesticide use include crop rotation, biological control, monitoring, economic thresholds, and resistant varieties.

Despite the success of IPM over the last 50 yr and major initiatives including the National IPM Initiative (1993 to 2000; GAO 2001) and the Strategic Agriculture Initiative (1998 to 2007; Sorensen and Greitens 2015), significant challenges remain to the practice and adoption of IPM (Tschirley 1984, Barfield and Swisher 1994, Ehler and Bottrell 2000, Ehler 2006, Peterson et al. 2018). Efforts to increase IPM adoption have been hindered by poor coordination and prioritization of IPM strategies and a lack of a clear methodology to measure IPMs environmental and economic benefits (GAO 2001, Greitens and Day 2007). Likewise, one often cited benefit of IPM is pesticide reduction, but in many cases, IPM may fail to reduce pesticide use or even increase it (Norton and Mullen 1994, GAO 2001, Maupin and Norton 2010). Another challenge has been communication with the general public. While IPM is virtually unknown by the general public, USDA Organic is well known to consumers largely due to social advocacy and promotion.

Another challenge, despite efforts at promoting IPM, is that much of America's broad-acre row crops (such as corn and soybean) falls victim to reliance on shock and awe pest management (Hurley 2016), a strategy that effectively results in the use of pesticides (or genetically modified pest resistant varieties) regardless of whether the targeted pests are likely to result in economically significant losses. This strategy results in a rapid loss of effective management products through evolution of pesticide resistance. As Hurley (2016) indicates, there is a need to balance the short-term benefits of effective pest management against the need for pesticide conservation (or product stewardship) and a similar need to balance benefits against other costs associated with pesticide use.

Despite these issues, IPM remains the most important pest management strategy for delivering positive environmental outcomes on the 99% of American agricultural acreage that is nonorganic (Greene 2013). Since IPM remains so critical, efforts should continue to deliver IPM to stakeholders. In this article, we provide what we hope are useful insights from the field of Social Ecological Systems (SES) (Resilience Alliance 2017) as a method to improve crop pest management in the future, including the delivery of IPM, while reducing negative social and environmental impacts. An SES frameworks have allowed researchers to understand how social behavior influences the resilience and vulnerability of systems, such as fisheries, rangelands, and forests (Bodin and Norberg 2005, Smith et al. 2008, Armitage et al. 2009, Rasch et al. 2016) that would not be explained by ecological factors alone. First, we review the complexity of crop pest management from the social perspective; second, we reframe this complexity as an SES; and third, we showcase SES tools for understanding the complexities of crop pest management.

Pest Management Is a Complex Social System

Pest management is a complex system of ecological processes and social actors including a number of key facets (Fig. 1). First, grower decision making is more strongly influenced by market forces and pesticide marketing than it is by IPM recommendations (A in Fig. 1). Pest management decisions are recommended by crop consultants who scout fields and monitor weather and pest traps, but this does not implicitly lead to pesticide reduction. Many growers rely upon extension to provide IPM guidance in the form of pest alerts, forecasts, and monitoring, but the decline in extension service funding (Wang 2014) may make growers more dependent upon advice from agricultural company salespeople. Second, pest pressure as a result of selection pressure, resistant genotypes, and emerging pests (such as Spotted Wing Drosophila, *Drosophila* suzukii Matsumura) is not constant but tends to increase over time (B in Fig. 1). The combination of (A) and (B) may cause growers to use more pesticides (D in Fig. 1) over IPM-based systems (C in Fig. 1) resulting in costs to human health and the environment (E in Fig. 1). The estimated damage to the environment and society caused by pesticides in the United States is between $10 and 35 billion/yr (Pimentel and Burgess 2014, Bourguet and Guillemaud 2016). This includes impacts on wildlife, pollinators, and human health. When a grower makes a decision to spray or not, these external costs of pesticide application rarely factor into the decision-making process. Public concern over these impacts may lead to the deregistration of critical pesticide products, which help ensure a reliable and low-cost food supply. Loss of pesticide efficacy (F in Fig. 1) results in crop losses (G in Fig. 1), which, in turn, leads to research and extension efforts (H in Fig. 1) to reduce these losses and pesticide environmental impacts. It should be noted that a lag period often exists between the intensification of a problem and the appearance of publications proposing solutions.

Research, especially on pesticide environmental impacts, is picked up by the media and environmental groups (I in Fig. 1), who lobby government agencies (J in Fig. 1), and in some cases litigate to enact regulatory changes that restrict or discourage pesticide availability and use. An example: the insecticide sulfoxaflor was approved by the EPA, but environmental groups sued the EPA to prevent its registration (Gillam 2015). A second example that emerged in 2018 is the presence of glyphosate in breakfast cereals made from oats in a research study conducted by an environmental lobby group (Zaveri 2018). This study will likely decrease the social acceptance of glyphosate use and could result in eventual regulatory changes. Likewise, the agriculture and food industries lobby government to keep pesticides registered and minimize regulations (K in Fig. 1.) The lobbying power of the Agrochemical industry has likely increased in recent years, especially with consolidation into four major agrochemical companies.

Some agricultural companies also market farm management systems, for example, Maglis (BASF), FieldView (Monsanto), and AgriEdge Exclesior (Syngenta) (Pham and Stack 2017), which provide a packaged approach for growers to select seeds, fertilizers, pesticides, and postharvest products using precision agriculture technologies including advanced analytics. This vertical integration of production renders growers unable to choose IPM tactics, if they are not mandated by the companies for which they are contracted,

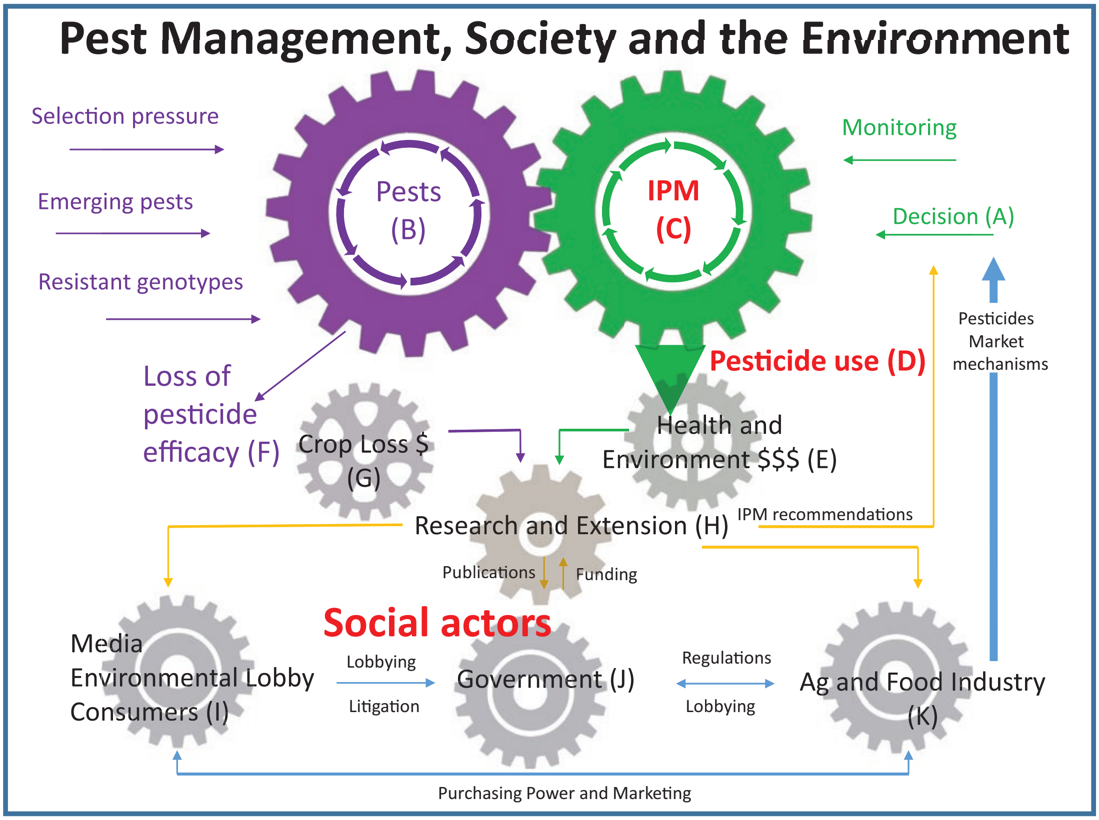

Fig. 1. Interactions of pest management with society and the environment.

further pushing grower decisions (A in Fig. 1) toward strategies that benefit the Agricultural and Food industries (K), not necessarily pesticide reduction. On a positive note, market-based mechanisms have been successful in promoting IPM and reducing pesticide use. Since 1998, the IPM Institute has been developing IPM practices for specific crops and regions, many of which can be found in the National IPM database. Working with food industry entities, such as supermarkets, restaurant chains, wholesalers, etc, the IPM institute has set up market-based programs where growers agree to IPM practices in order to be eligible to supply these food companies. The food companies benefit by being able to market their products as ecologically friendly and consumers (I in Fig. 1) benefit (presumably) from lower pesticide residues and are empowered with information to use their purchasing power to support practices that are expected to reduce pesticides. Such market-based mechanisms are widely used in Europe (Lamine 2011).

Understanding and predicting the behavior of the whole pest management system (Fig. 1) seem difficult, given the large number of social actors and the complex interaction of ecological and social processes. In particular, we note that disturbances in the system such as the overuse of a class of pesticides with consequential increases in pesticide resistance, environmental impacts, and social acceptance may involve a considerable lag time before the system corrects or reorganizes. This is represented by Fig. 1 as a complex system of problem discovery, scientific investigation, lobbying, and finally, regulations either by the government or self-regulations by the industry. Whereas IPM provides an avenue for more rapid system self-correction, our efforts to improve IPM adoption often fall short of desired outcomes in part because the system does not economically reward IPM adopters, even as the benefits accrue system wide. To address these complex issues, we propose reframing the complexity of Fig. 1 in terms of an SES, so that tools and insights from this field can be used to improve pest management and the adoption of IPM.

Reframing Pest Management as an SES

Before describing what SES are, we give an example of their application: bioeconometric modeling of a gag (a slow growing grouper) fishery (Smith et al. 2008). Whereas biological intuition and simulations based on fish life histories alone suggest that a spawning season closure will reduce fishing pressure and increase stocks; an SES approach that also accounts for the behavior of the fishing fleet based on economic conditions, such as price, biomass, and regulations, shows that these intended outcomes of the spawning closure do not materialize. The gag econometric model was validated with data of fish stock numbers. Once validated, the model can estimate the impact of new rules and regulations such as quotas and daily trip limits. The modeling tool can demonstrate to stakeholders which regulations promote healthy fish stocks, and thus provide a powerful tool to broker compromise solutions to contentious problems in fisheries management. Overall, utilizing the SES framework allows researchers to understand how social behavior influences the resilience and vulnerability of systems such as fisheries that would not be explained by ecological factors alone.

An SES can be defined as a system that includes 1) biophysical and social factors that interact in a resilient, sustained manner; 2) multiple spatial, temporal, and organizational scales; 3) critical resources (natural, socioeconomic, and cultural); 4) dynamic complexities that require adaptation; and 5) external social and biophysical factors (i.e., those factors that are outside of the system itself such as climate change or political forces; Redman et al. 2004). Crop pest management fits the definition of an SES in many ways (Fig. 2). 1) Biophysical factors of evolution of pesticide resistance, natural enemies, pest dispersal, and host diversity (Birch et al. 2011) and social factors of government regulations, market mechanisms, crop insurance, and research and extension interact through the affordability of food, pesticide residues in food, and pesticide pollution. If food is not affordable, social processes increase food production at the expense of environmental issues, such as pesticide pollution. Provided food is affordable, public concerns over pesticide pollution, and residues in food favor social processes that result in less pesticide use. Examples are neonicotinoids which are a pesticide technology not at risk of abandonment due to economic concerns, or of being displaced by an improved technology, but rather where arguably unnecessary use and potential negative environmental impacts (Douglas and Tooker 2015) led to a decrease in social acceptance. 2) Pest management is a multiscale phenomenon: while it has been historically practiced mostly at the farm scale, the impacts generated by pesticides and their residues on water, wildlife, and food are relevant at much larger spatial scales (Zalucki et al. 2009). 3) Critical resources include food and fiber that are products of agricultural systems. They also include clean air and water that can be polluted by agricultural activity including pesticide use. 4) Growers must adapt their pest management practices to maintain profitability in response to dynamic social and ecological processes, including emerging pests and climate change. 5) Finally, external social factors include commodity prices and agricultural regulations, and climate change is an external biophysical factor.

Although the complexities of an SES can seem overwhelming, tools are available to help scientists understand their behavior and design strategies to improve social and environmental outcomes.

Tools for Understanding SES

Although SES can be inherently complex, a number of tools, such as heuristics and modeling, have been developed to help explain their behavior. A heuristic is a practical approach to problem solving that uses simple efficient rules to guide decision making (Albar and Jetter 2009). One of the most commonly used heuristics is a rule of thumb which allows a user to estimate and make an approximation without doing exhaustive research. Heuristics are particularly useful to understand complex systems for which optimal solutions may not be possible or easy to calculate. The complexities of an SES can be understood in terms of five heuristics: adaptive cycle, panarchy, resilience, adaptability, and transformability (Table 1; Walker et al. 2004, Resilience Alliance 2017). Each of these heuristics provides a framework for understanding how SES change over time and what factors mediate these changes. Pesticide resistance has been described as a 'wicked problem' that can outstrip the ability to replace outmoded chemistries (Gould et al. 2018). Heuristics can be applied to understanding pesticide resistance in terms of adaptive cycle, panarchy, and resilience (Hoy 2008). The *adaptive cycle* has four distinct phases: growth or exploitation, conservation, collapse or release, and reorganization. This can be used to explain the cycle of pesticide resistance in four steps: 1) new chemistry controls pests, 2) highly pesticide-dependent systems are created, 3) pesticide resistance causes crop loss, and 4) new pesticide chemistries and market opportunities develop (Hoy 2008). *Panarchy* is a framework of rules to understand an interacting set of adaptive cycles in a nested hierarchy (Resilience_Alliance 2017). Panarchy can explain how pesticide resistance problems begin locally and

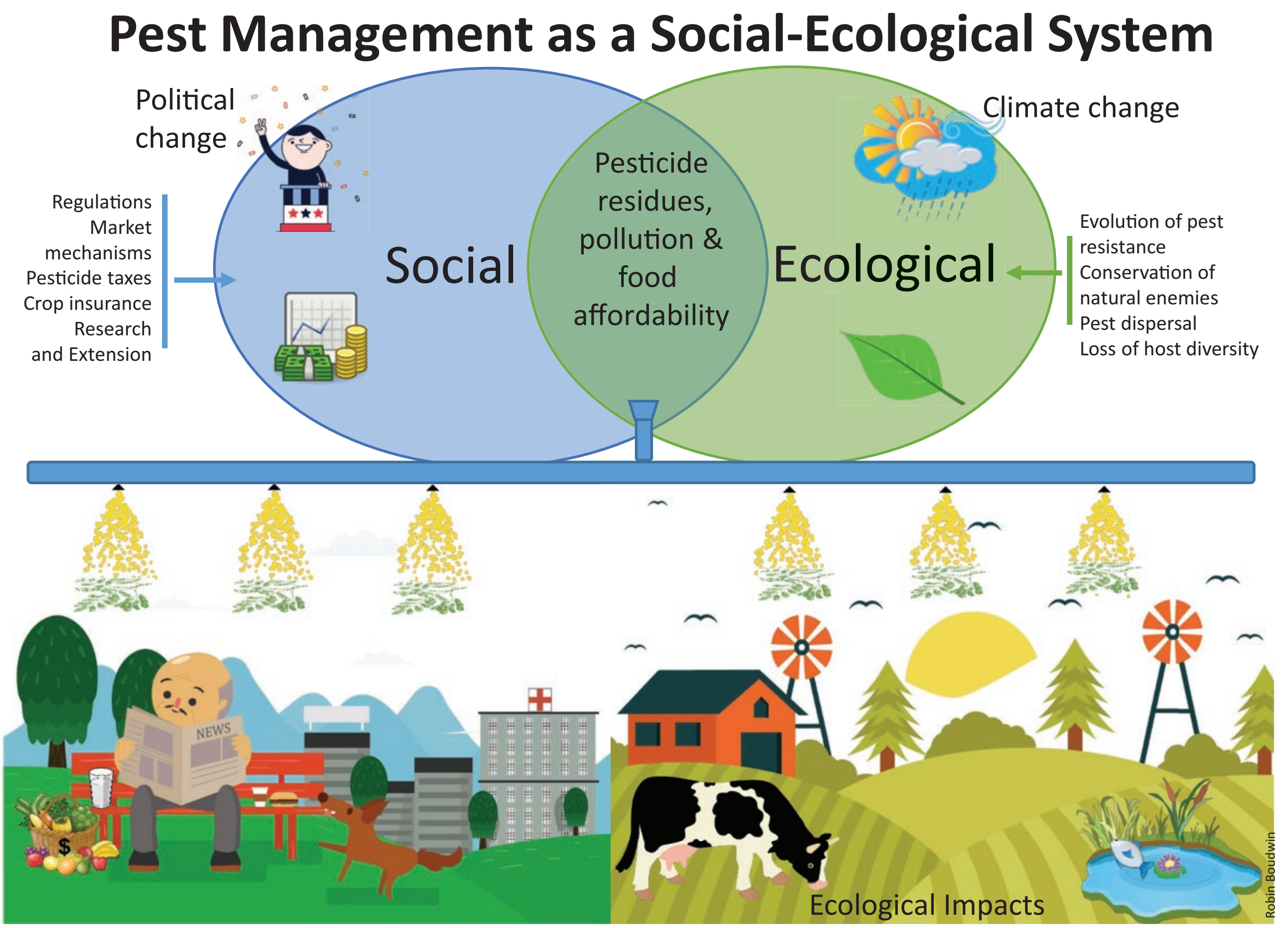

Fig. 2. Pest management as an SES.

Table 1. Definitions and applications of five heuristics including resilience, adaptive cycle, panarchy, adaptability, and transformability that provide insight into the dynamics of pest management as SES

Heuristic	Definition	Reference	Application
Resilience	The capacity to absorb or withstand disruption and the system's ability to self-organize, learn, adapt, and recover from a shock	Gunderson and Holling (2002), Walker et al. (2004), Folke (2006), Resilience_Alliance (2017)	Food security, climate change
Adaptive cycle	A dynamic cycle in the SES consisting of four distinct phases have been identified: growth or exploitation (r), conservation (K), collapse or release (omega), and reorganization (alpha)	Walker et al. (2006)	Pesticide resistance, biosecurity
Panarchy	A framework of rules to understand an interacting set of adaptive cycles in a nested hierarchy	Resilience_Alliance (2017)	Pesticide resistance
Adaptability	Adaptability is the capacity of the actors in a system to manage resilience.	Walker et al. (2006)	Eco-efficiency
Transfomability	The capacity to create a fundamentally new system when ecological, economical, and/or social conditions make the existing system untenable."	Walker and Salt (2012)	Biosecurity, climate change

scale upward, whereas solutions flow from innovation in research and development downward (Hoy 2008). As the problem scales, it intensifies in impacts, and solutions must be scale dependent. For example, pesticide resistance at an entirely local scale can easily be managed by switching products; regional-scale problems must be met by education, monitoring, and emergency registrations, whereas problems of national significance require more complex solutions, such as regulatory action or the development of new pesticides. *Resilience* is the capacity to absorb or withstand disruption and the system's ability to self-organize, learn, adapt, and recover from a shock (Gunderson and Holling 2002, Walker et al. 2004, Folke 2006, Resilience Alliance 2017). Resilience can be assessed by four factors: 1) degree of return—how close the return is to the initial stable condition; 2) return time—the time taken to reach the new stable level; 3) rate of return—the rate at which response returns to stable condition; and 4) efficiency—the total area under the response curve (Todman et al. 2016). These resilience measures have obvious application to pesticide resistance, that is, if a major class of pesticides is lost, estimating each of these four factors would provide valuable data on how much research and development effort should be expended to fast track alternative control products or strategies in order to improve resilience. Beyond pesticide resistance, heuristics could also have application to other important issues such as recovery from yield shocks caused by an invasive pest or by some other type of disruptor such as the loss of a class of pesticides through regulatory action.

Modeling is also a very useful tool for understanding SES (Schluter et al. 2012) and has potential applications for pest management including: 1) evaluating or developing socioeconomic mechanisms to improve IPM adoption and eco-efficiency (Picazo-Tadeo et al. 2011); 2) testing IPM strategies, especially at larger spatial scales (Zalucki et al. 2009); and 3) facilitating the adoption of IPM strategies through participatory modeling (Voinov and Bousquet 2010, Cook et al. 2016). A good example of the first application is the agent-based modeling of Thai vegetable growers to investigate if IPM and social mechanisms (such as biopesticide subsidies) could reduce pesticide use (Grovermann et al. (2017). Their model considered choice of pesticide treatments based upon anticipated pest intensity, costs, toxicity, and efficacy of pesticides, IPM programs, commodity prices, and other input costs, such as labor and the rate of diffusion of innovation. The model evaluated changes in farm profits, program costs to government sponsors, and pesticide use. The findings were that a policy combining integrated pest management, a progressive pesticide tax based on toxicity, and subsidies lowering the price of biopesticides could reduce the average use of hazardous pesticides by 34% without adverse effects on average farm income.

A second example of modeling within the context of SES is the local adaptive management of natural resources and pest outbreaks using agent-based modeling (Bodin and Norberg 2005). In simulations, agents were given the task of managing the proportion of land that was allocated to natural vegetation, which harbored natural enemies and the proportion of land that was cropped. The simulation investigated the transition from stable high-yield returns to occasional catastrophic crop losses. One of the factors that influenced this transition was the density of farms. Isolated farms where unable to avoid crises in the long run, whereas high-density networks tended to have highly synchronized behavior that resulted in occasional large-scale crises. In contrast, low-to-medium density networks that represent loosely coupled management units proved to be the most resilient to crises. This kind of simulation has obvious implications as a participatory modeling tool to demonstrate the importance of refuge management and to test the most effective management strategies, including their effectiveness at multiple scales. An example of such a participatory modeling exercise is an agent-based model for exploring best management responses to fire blight invasion in pome fruit (Cook et al. 2016). This analysis was done at a relatively small spatial scale, two townships in the Goulburn Valley, and included functions that accounted for dispersal of the pathogen by bee vectors and rain. The model accounts for the area of production that is impacted by the pathogen invasion and can estimate the costs associated with an eradication or quarantine program. The tool can be used to demonstrate to stakeholders the potential costs and outcomes of various management options such as tree removal radius and owner reimbursement costs and to help them reach a consensus on best management options (Liu et al. 2015). These few examples of SES tools suggest that there is potential to gain insights for improving pest management in the future.

Conclusions

We believe that in the United States while food remains affordable, the political, regulatory, and research agenda will increasingly be driven by environmental and human health issues. In this paper, we have already mentioned three examples that highlight this trend, litigation against the insecticide sulfoxaflor, glyphosate residues in cereals, and public concern over the environmental impact of neonicotinoids. Developers of IPM strategies have long understood that embracing ecological principles has been critical for the long-term success of pest management. Now in the 21st century, the understanding of how social and ecological processes work together will be critical for the future success of pest management. This paper outlines SES techniques including heuristics and modeling that offer potential to give fresh insights on pest management including: 1) pest management environmental efficiency, especially at multiple scales; 2) incentives for adopting IPM; 3) the stewardship of pesticides; and 4) the resilience of pest management strategies and tactics. Finally, we hope the insights in this paper will prompt ideas for future research that can improve the social acceptability of pest management in the future.

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