Stewardship Challenges for New Pest Management Technologies in Agriculture

Authors:

Dr. David R. Shaw (Chair)
Mississippi State University
Mississippi State, MS

Dr. David E. Ervin
Portland State University
Portland, OR

Dr. Raymond A. Jussaume, Jr.
Michigan State University
East Lansing, MI

Dr. George Frisvold
University of Arizona
Tucson, AZ

Dr. Gregory A. Sword
Texas A&M University
College Station, TX

Reviewers:

Amy Asmus, CCA RMS
Asmus Farm Supply
Rake, IA

Dr. Terrance M. Hurley
University of Minnesota
St.Paul, MN

Dr. Clinton D. Pilcher
Corteva Agriscience
Johnston, IA

Dr. Jill Schroeder
New Mexico State University
Las Cruces, NM

CAST Liaison: **Dr. Melissa Johnson**
Corteva Agriscience
Indianapolis, Indiana

Introduction

Technology is a key enabler of more efficient agricultural production as growers attempt to meet the cost-effective need for increased food, fiber, and bioenergy, while managing limited inputs, conserving valuable natural resources, and protecting environmental quality. Each new pest management technology (weed, insect, disease) developed brings a number of benefits and risks—environmental, health, resistance—that must be considered and managed through effective stewardship practices to ensure that benefits are fully realized while risks are minimized. Best stewardship practices for some new technologies have not been fully or effectively adopted, resulting in reduced effectiveness over time, and in some cases, negative environmental impacts.

Stewardship is the careful and responsible management of something entrusted to one's care. Three basic questions embedded in the definition of stewardship are crucial to answer in crafting improved stewardship policies for pest management technologies in agriculture:

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- What constitutes "careful and responsible" stewardship?
- What are the contents of "something entrusted"?
- What parties hold responsibility for exercising "care"?

The goal of stewarding new pest management technologies is to further sustainable agriculture. A National Academy of Sciences report (NRC 2010b) states that "improving sustainability is a process that moves farming systems along a trajectory toward meeting various socially determined sustainability goals as opposed to achieving any particular end state." The panel argued agricultural sustainability embodies four generally agreed goals:

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- Satisfy human food, feed, and fiber needs, and contribute to biofuel needs
- Enhance environmental quality and the resource base
- Sustain the economic viability of agriculture
- Enhance an equitable balance in the quality of life within social groups, including farmers, farm workers and society as a whole

The definition implies that developing sustainable pest management requires integrated contributions from the natural and social sciences using interdisciplinary and transdisciplinary approaches that engage all stakeholders (i.e., farmers, industry, consumers, and others) to understand the diversity of objectives, priorities and constraints that shape that pursuit. Conducting such a systems-based process will help reveal the synergies and tradeoffs among the four goals. This commentary is framed in that context and will:

- Identify and explore the stewardship challenges of new pest management technologies for both growers and technology developers, and
- Address the roles of different stakeholders in the successful stewardship of these technologies.

Improved clarity and visibility of the barriers to implementation of stewardship requirements can aid the development of regulations for new technologies that take into account grower and farming system needs, while at the same time protecting the various stakeholders and ecosystems.

Benefits of New Agricultural Technologies

The ability to feed and clothe a growing human population has relied upon agricultural innovation for centuries, and will continue to do so. Part of the response to these challenges involves the development of new technologies and their integration into current practices. The commercialization and widespread global adoption of genetically modified (GM) crops (also called genetically engineered crops) that began in 1996 provides many excellent examples of the benefits that can arise from the development and use of new agricultural technologies. These crops revolutionized insect and weed pest management, and their dissemination in modern agriculture has been described as the fastest adoption of any agricultural practice in human history (ISAAA 2017; Khush 2012). As of 2017, GM crops were grown in 24 countries by 17 million farmers across almost 190 million hectares (ISAAA 2017). GM crops were planted on approximately 15% of global cropland in 2017, suggesting the importance

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of devising sound economic, environmental, and social stewardship policies to enable future growth (ISAAA 2017). The list of GM crops being developed continues to grow, but has been dominated from the beginning by soybean, corn, cotton, and canola commodities that play a major role in international agricultural trade. In the United States, herbicide-resistant GM soybean, corn, and cotton are now grown on more than 90% of acres planted to those crops, with insect-resistant GM corn and cotton planted on roughly 80 to 85% of acres of those crops (USDA 2019).

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The rapid adoption of GM technologies by growers across the world reflects the many benefits to farmers associated with the cultivation of GM crops that have been documented over the past quarter century. Benefits arising from the use of both insect-resistant and herbicide-resistant GM crops can be credited to reductions in overall pesticide use, increasing yields, labor savings and associated changes in management and land use practices, such as reduced tillage. A large number of detailed studies have documented the variety of environmental, economic, and health benefits to growers and society that are associated with the introduction of GM crops. Readers are referred to comprehensive assessments of the benefits and risks of GM crops by two recent National Academies of Science panels for more in-depth analyses (NRC 2010, 2016).

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One example is insect-resistant crops that have been engineered to express genes from the common soil bacterium, *Bacillus thuringiensis* (Bt); these genes express bacterial proteins that are toxic to insects. These proteins have the advantage of selectively targeting specific insect groups such as beetle or caterpillar pests, and when expressed in GM plants, are directly consumed by the pests themselves, further enhancing their specific activity (Sanahuja et al. 2011; Tabashnik and Carrière 2017). Several studies have shown that the widespread adoption of Bt crops can reduce population sizes of target pests and associated damage across large areas, with pest suppression benefits extended to growers not planting Bt crops (Carrière et al. 2003; Dively et al. 2018; Hutchison et al. 2010; Wan et al. 2012; Wu et al. 2008; Zhang et al. 2018). The use of insecticides to control pests targeted by Bt crops has fallen as pest populations are reduced, with substantial reductions around the world in both the frequency and amount of insecticides applied (Henneberry and Naranjo 1998; Huang et al. 2010; Perry et al. 2016; Pray et al. 2001; Subramanian and Qaim 2010).

Bt crops also enabled a shift to the use of less toxic and more selective insecticides to manage the other pests that are not specifically targeted by Bt proteins (Frisvold and Reeves 2010; Naranjo and Ellsworth 2009). Taken together, the reductions in insecticide use and toxicity associated with Bt crops has promoted the conservation of natural enemies in agroecosystems, thereby contributing to the integrated management of both target and non-target insect pests (Romeis et al. 2019). Bt crops can also play a central role in the eradication of crop pests, thereby removing the need for insecticide use altogether, as seen in the use of Bt cotton as a key part of the successful pink bollworm, *Pectinophora gossypiella*, eradication program in the southwestern United States (Carrière et al. 2003; Naranjo and Ellsworth 2010).

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In addition to reducing the need for insecticides, Bt crops can also help reduce the incidence of toxin-producing fungi that colonize plants after they are damaged by insect feeding (Hammond et al. 2004). The mycotoxins, fumonisin

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and aflatoxin, are produced as secondary metabolites by certain species of *Fusarium* and *Aspergillis* fungi that have been linked to a number of detrimental health effects on humans and livestock including liver failure and cancer (Wu 2006). Several studies have highlighted the economic and health benefits of Bt corn in reducing food contamination by these fungi (Carzoli et al 2018; Ostry et al. 2010).

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GM crops introduced in 1996 that were resistant to the broad spectrum herbicide, glyphosate, have benefitted producers by providing flexibility of application and increased profits while managing difficult weed problems. As with Bt crops, many of the environmental benefits of herbicide-resistant crops also has come from reductions in the amount and toxicity of herbicides used for weed control (Frisvold and Reeves 2010; Smyth et al. 2011; Smyth 2017). For example, although glyphosate use has increased with the adoption of glyphosate-resistant varieties, its chronic toxicity is much lower than most other herbicides available in the United States. As such, should its use be replaced by other currently available products, an overall increase in chronic toxicity associated with an increase in the use of more toxic herbicides would be expected (Kniss 2017).

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The efficacy and flexibility offered by herbicide-resistant crops not only saves growers time and money, but also provides opportunities to alter cultivation practices such as the use of tillage to manage weeds. Reduction in weed pressure has facilitated an increase in the use of no till or reduced tillage (Givens et al. 2009; Smyth et al. 2011; Zilberman, Holland, and Trilnick 2018). These practices promote sustainability in agricultural practices associated with GM herbicide-resistant crops by decreasing erosion, greenhouse gas emissions, soil moisture loss, runoff, and water and air pollution, while increasing carbon sequestration and promoting agroecosystem stability that conserves natural enemies for biological control of pests (Barrows, Sexton, and Zilberman 2014a; Brookes and Barfoot 2018; Smyth 2017; Smyth et al. 2011; Romeis et al. 2019).

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Economic benefits to both producers and consumers have been repeatedly documented since the introduction of GM crops (Klümper and Qaim 2014; Smyth 2017). Brookes and Barfoot (2017) provide a comprehensive assessment of the economic impacts of the four main GM crops (corn, soybean, cotton, and canola) over the first 20 years of their use. They estimated that by 2015, GM crops were providing more than $15 billion in annual economic benefits, with cumulative global economic benefits valued at $167 billion since their initial introduction. Importantly, these benefits were distributed evenly between developed and developing countries. Gains in the economic dimension of sustainability associated with GM crops could be attributed to yield increases, with the remainder coming from cost savings. A 2010 comprehensive assessment of the farm-level sustainability of GM crops in the United States says:

> "Farmers who have adopted GE crops have experienced lower costs of production and obtained higher yields in many cases because of more cost-effective weed control and reduced losses from insect pests (NRC 2010)."

Note that the positive yield and cost effects were not found in all farm situations. The next NRC assessment of GM crops offered this general conclusion:

"Bt crops have increased yields when insect pest pressure was high, but there was little evidence that the introduction of GE crops were resulting in a more rapid yearly increases in on-farm crop yields in the United States than had been seen prior to the use (NRC 2016)."

The findings by the NRC panels suggest that the yield effects of GM crops will not be uniform across crops, farming operations and over time as growing conditions change. Such heterogeneity has important implications for understanding the equity dimensions of GM crops as well as developing effective stewardship programs of pest management technologies as explored below.

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Consumers have benefitted through lower prices, with the costs of soybean, cotton, and corn estimated to be 33%, 18% and 13% lower, respectively, in comparison to what they would be without the advantages of GM technologies (Barrows, Sexton, and Zilberman 2014b). Intuitively, it makes sense to think that increasing agricultural production to support a growing population would require a commensurate increase in the amount of land under cultivation. However, the fact that higher yields on the same amount of land can be achieved through the use of some GM crops provides the additional benefit of increasing productivity while reducing the need for new land to be brought into production (Zilberman, Holland, and Trilnick 2018). For example, the ability to avoid pre-emergence herbicide treatments early in the season when growing herbicide-resistant GM crops can extend the growing season long enough to support two successive crops (Barrows, Sexton and Zilberman 2014a,b; Monzón et al. 2014; Trigo and Cap 2003). This scenario illustrates compounded benefits of GM crops in which an increase agricultural sustainability is combined with increases in both production and potential economic gains to farmers.

Risk Management for GM Crops

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Table 1 lists some risks associated with GM crops (Bt and HR) in the leftmost column. The middle column lists legal and regulatory measures intended to address these risks. The rightmost column lists voluntary measures that growers can take to reduce these risks. While various federal regulations determine whether GM crops may be produced at all, Table 1 focuses on the risks and responses associated with how GM crops are managed. In addition to regulations and voluntary actions to reduce risks, some risks (such as off-target movement of pesticides) have been addressed through lawsuits. The information in Table 1 helps define what human behavior amounts to "careful and responsible" stewardship of new pest management technologies.

Risk	Legal / Regulatory Measures	Stewardship / Voluntary Measures
Resistance	Refuge requirements; Mode of action (MOA) and other product labeling requirements; Resistance management plan requirements for pesticide registrants	Adoption of IPM and resistance management practices
Off-target movement of pesticides	Negligence standard of liability; State drift laws; Trespass law	Pesticide drift plans; Implement conservation practices and IPM techniques; Evaluate wind and weather; Use appropriate equipment; calibrate and use equipment correctly, train operators
Worker safety	Field re-entry rules; Application instructions; Applicator certification; Protective clothing requirements; Worker protection standards; Federal certification standards for pesticide applicators	Applicator training; Appropriate equipment; Calibrate equipment; Autonomous equipment
Risks to beneficial insects	Regulation of movement of beneficial insects; Product labeling requirements to reduce risk to beneficial insects	Integrated pest management and conservation practices;
Gene flow	Field trial rules; Planting restrictions; Seed certification	Field isolation; Buffers; Differential planting or harvesting dates; Crop rotation
Risks to water quality	Surface, drinking, and groundwater monitoring requirements	Riparian buffers; Adoption of pest and sediment management systems
Risks to pollinators	Apiary registration requirements; Exclusionary rights for hive placement; Restrictions on time and location of pesticide applications	Conservation easements; Conservation programs; Beneficial organism protection best management practices

Table 1. Risks, regulatory and stewardship measures.

Barriers to Adoption of Stewardship Practices

A “weed” is purely a social construct since, for example, a corn plant in a corn field is not a weed, but a corn plant in a soybean field is.

A *social construction* is defined as an idea or practice that a group of people decide upon as being real and that, over time, comes to be taken for granted by that group. For example, while weeds are plants with specific biological characteristics that insure success as pests, the fact that a specific plant species is a "weed" is also socially determined, and thus is a *social construction*. This idea that weeds are *social constructed* can be appreciated by reflecting upon traditional definitions of a weed, which have ranged from “a plant growing where it is not wanted,” to “plants which are a nuisance (to humans),” to “a plant whose virtues have not yet been discovered” (Harlan and de Wet 1965). A 'weed' fits the definition of a social construct since, for example, a corn plant in a corn field is not a weed, but a corn plant in a soybean field is often referred to as a weed.

Weed resistance to herbicides is an evolutionary response to human efforts and technologies that have been designed to eliminate plants that humans agree are undesirable.

In other words, what is a weed and ideas as to how to best manage them are not simply biological or technological problems, they are also *social problems.* Weed resistance to herbicides is an evolutionary response to human efforts and technologies that have been designed to eliminate plants that humans agree are undesirable. This decision and resulting actions are done so that other plants that are considered to be more desirable can grow in abundance. In other words, integrated pest management should be seen as a social process that involves the interaction of social groups with natural systems. Thus, the problem of weed resistance to herbicides can be considered as a problem that has no permanent or easy solution, in large part because working to address the problem requires recognizing the interaction of multiple social, natural, and technological issues. This interaction must be taken into account when thinking about effective stewardship measures.

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Unfortunately, agricultural production problems like managing weeds have come to be viewed by many as primarily biological and/or technological in nature. In other words, weed resistance has come to be *socially constructed* as being primarily a technological issue that can be solved through the discovery and application of the next new technological fix. As with all social constructs, many different parties such as chemical companies, the financial sector, and research/extension personnel have likely played contributing roles to the evolution of weed resistance. Many, although certainly not all, agricultural producers also share a socially constructed optimism in relying on new technological solutions, i.e., techno-optimism (Dentzman, Gunderson, and Jussaume 2016). This became apparent in both qualitative and quantitative research. In a series of focus group interviews conducted in 2015 in Arkansas, Iowa, Minnesota, and North Carolina, farmers were asked about the perceptions of weed resistance and how they were planning on responding to the evolving problem (Jussaume, R. 2015. Personal communication). What became quickly apparent is that many farmers were not only highly dependent on technological solutions to weed management problems, but that they were counting on the development of new technologies to address the problem of weed resistance.

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This is exemplified by the quotes below that came from three separate interviews:

> Participant: “In other words, trying to keep a company keeping new products moving in the pipeline – because that’s what’s eventually is going to have to happen is…this is never going to go away.

> You’re always going to have an issue with whatever herbicide comes out. So, keeping new options coming is more important than really the agricultural practices and all that.”

Surveys were received from farmers in 28 different states, with 41% of the completed questionnaires coming from farmers in Arkansas, Iowa, Illinois, Minnesota, Nebraska, and Texas. The survey revealed that farmers use a wide array of practices, but the most common were herbicide mixes and multiple herbicides.

> Participant 1: "I'm a little discouraged with the chemical industry. I think -- I don't think they're looking at the opportunity…I think it just -- I think the chemical company just rolled over and held her hands up. [They] just want to throw some 2,4-D at it. What? That's baloney. Those people are supposed to be intelligent. Well, duh."
> Participant 2: "I agree, totally."
> Participant 3: "You can't tell me that it can’t be done. You can't tell me that there ain't a chemical out there to kill that weed. I will never believe it."

> Participant 1: "Well, the one thing that we don't know anything about is what new chemistry is coming. But the more that we have resistance, the harder they're going to work to find something. […] We’re too big of an industry not to.”

The insights gained from these focus groups were used to develop a self-reported internet and mail survey on farmer weed management practices and attitudes. Surveys were received from farmers in 28 different states, with 41% of the completed questionnaires coming from farmers in Arkansas, Iowa, Illinois, Minnesota, Nebraska, and Texas. The survey revealed that farmers use a wide array of practices, but the most common were herbicide mixes and multiple herbicides. This is particularly true for those who must manage large acreages. Table 2 reveals that farmers are much more likely to use herbicide-based practices on more than 60% of their fields, than non-herbicide based practices. In addition, those who manage more than 500 acres are significantly more likely than those who manage less than 500 acres to use herbicide-based practices. A majority of farmers do not use practices like inter-row cultivation, high planting densities, cover crops or mulches, and special planting date. This could be an example of farmers, in the context of needing to use multiple weed management approaches, using heuristic devices to simplify farm management decision-making (Mortensen et al. 2012; Zwickle, Wilson, and Doohan 2014).

Farmers must simultaneously manage for weeds, pests, soil fertility, erosion, and other problems while responding to constantly changing weather conditions, public policies, and recommendations from experts.

The dependency on herbicide-based practices is quite understandable given the size of modern farming operations, as well as the complexity of management issues that farmers face. Farmers must simultaneously manage for weeds, pests, soil fertility, erosion, and other problems while responding to constantly changing weather conditions, public policies, and recommendations from experts. In other words, integrated stewardship is highly complex, time consuming and often costly, and thus, anything that can help farmers simplify their management approach is helpful and desirable in their eyes. Unfortunately, and as the evolution of weed resistance has demonstrated, nature is characterized by heterogeneity and complexity (Budzynski 2017), and integrated stewardship must necessarily recognize the complexity of agricultural production systems.

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While growers or the pest management professionals they hire make the most direct decisions affecting these risks, many others play critical roles in managing pest control risks. These include agricultural input suppliers, government agencies, Cooperative Extension, land grant universities, professional societies, and producer organizations (Coble and Schroeder 2016).

	Do Not Use at All	**Use on < 60% of fields**	**Use on > 60% of fields**
Herbicide-Based Practices			
Pre-Emergent Herbicide*	17.9% / 7.8%	22.2% / 17.0%	59.9% / 65.2%
Post-Emergent Herbicide*	9.0% / 5.0%	16.1% / 11.2%	74.9% / 83.8%
Post-Harvest Herbicide*	71.2% / 52.4%	21.0% / 32.3%	7.8% / 15.3%
Herbicide Mixes*	14.1% / 5.4%	19.9% / 14.1%	66.0% / 80.5%
Multiple Herbicides*	14.8% / 4.7%	18.8% / 15.3%	65.4% / 80.0%
Use Full Label Rate*	10.1% / 5.6%	19.8% / 14.7%	70.1% / 79.7%
Rotate MOAs Annually*	28.8% / 13.2%	29.6% / 28.1%	41.6% / 58.7%
Non-Herbicide-Based Practices			
Inter-Row Cultivation	79.4% / 77.8%	13.2% / 15.6%	7.4% / 6.6%
Tillage*	34.6% / 24.8%	30.7% / 34.2%	34.6% / 41.0%
Crop Rotation*	15.2% / 6.5%	21.4% / 22.3%	63.4% / 71.2%
High Planting Densities*	51.4% / 49.8%	24.1% / 33.9%	24.5% / 16.3%
Hand Weeding*	48.0% / 41.4%	39.5% / 50.6%	12.5% / 7.0%
Cover Crop or Mulches	64.2% / 60.4%	23.4% / 30.7%	12.4% / 8.9%
Special Planting Date	60.7% / 59.7%	23.0% / 27.0%	16.3% / 13.3%
Narrow Rows	40.5% / 39.1%	14.4% / 22.2%	45.1% / 39.7%
Weed Maps	85.2% / 83.7%	9.0% / 11.6%	5.8% / 4.7%
(< 500 acres / > 500 acres)			

Table 2. Extent of Weed Management Strategy Use by Size of Farm
**Indicates that the differences in %'s between columns is significant at a 5% or less*

Examples of Successful Stewardship Programs

Area-wide Codling Moth Control

A three-year Cooperative Pear IPM Project supported by the USDA and involving collaboration between the USDA, University of California Cooperative Extension, and growers in 1973 led to greater understanding of the role of natural enemies in pear IPM, improved pear quality, and chemical cost savings. Yet, by the late 1980s, California codling moth populations had evolved resistance not only to azinphos-methyl (AZM), but also to insect growth regulators, pyrethroids, carbamates, and chlorinated hydrocarbons (Weddle, Welter, and Thomson 2009). Even though annual insecticide application rates rose from 1.5 to 6 pounds per acre, growers still suffered economically significant fruit damage (Weddle, Welter, and Thomson 2009).

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By the early 1990s, University of California researchers had demonstrated that pheromone-based mating disruption could be effective at controlling the codling moth, when used in conjunction with limited insecticide sprays.

Mating disruption combined with limited insecticide applications improved pest control. As moth populations declined, growers were able to switch to more selective pesticides and to reduce total applications further.

By 2008, many pear orchards in the area went from applying 14 “high-risk’ active ingredient insecticides to applying 5–6 (primarily organic or reduced-risk) compounds. The shift from reliance on organophosphate applications to mating disruption saved growers \$100–\$208 per acre in costs.

By the early 1990s, University of California researchers had demonstrated that pheromone-based mating disruption could be effective at controlling the codling moth, when used in conjunction with limited insecticide sprays. Research also stressed monitoring of both target pest and secondary pest populations. A stakeholder group consisting of university research and extension professionals, a small number of growers (initially), private industry (developing pheromone delivery technology), pest control advisors, and fruit processors initiated an area-wide codling moth control program (Weddle, Welter, and Thomson 2009). This Randall Island Pilot Project was supported by grower group funding and relied on pheromone-mediated mating disruption. The Randall Island area bordered the Sacramento River on one side and fields of non-host crops for codling moth along much of the area’s perimeter. This helped delineate areas of control. Mating disruption combined with limited insecticide applications improved pest control. As moth populations declined, growers were able to switch to more selective pesticides and to reduce total applications further. Throughout the life of the project there was continuous resistance monitoring.

By the end of this project, codling moth trap captures fell by more than 90%, and a single pesticide application was sufficient to reduce damage to less than 0.2%. After the first year of implementation, organophosphate applications fell by 70 to 80%. Within two years, 90% of Bartlett pear acreage in the Sacramento Valley followed this mating disruption program (Weddle, Welter, and Thomson 2009). By 2008, many pear orchards in the area went from applying 14 “high-risk’ active ingredient insecticides to applying 5–6 (primarily organic or reduced-risk) compounds. The shift from reliance on organophosphate applications to mating disruption saved growers \$100–\$208 per acre in costs (Farrar, Baur, and Elliott 2016).

Technological and institutional factors involving both the private and public sectors contributed to program success. Experienced private pest control advisors (PCAs) were already in place because of earlier IPM efforts. Reliable and cost-effective pheromone mating-disruption products were tested and became commercially available. Growers were organized in a clearly defined area with a shared codling moth population. This network also shared a common dataset collected by a neutral party. Growers and PCAs then had common experiences of success that could be shared with and extended to surrounding growers.

While a cover spray of AZM was standard practice during the first year to increase the effectiveness of mating disruption, a cover spray was usually not needed for the second generation (Weddle, Welter, and Thomson 2009). The program included sterile insect release, parasitoid release, Bt sprays for secondary pest control, and an incentive program to encourage adoption of mating disruption techniques. Greater natural enemy populations improved control of secondary pests, saving growers the costs of chemically treating for them.

In 1995, the initial Randall Island success was expanded to a multi-state suppression program, supported and administered by the USDA’s Agricultural Research Service (ARS) and involving land grant universities in California, Oregon, and Washington (Calkins and Faust 2003). This 5-year program also emphasized mating disruption, reduction of organophosphate use, and coordinated grower efforts across large, definable areas. Participation expanded over the program's lifetime from 66 to more than 400 growers, with participating acreage increasing from 2,600 to nearly 21,000 acres. Both pear and apple production were included. The program featured collaboration between Federal agencies, university research and extension, State departments of agriculture, individual growers, commodity organizations, and private industry (e.g., packing houses and farm supply companies).

Five test sites were originally chosen, with growers contributing to research efforts. (Calkins and Faust 2003). Coordinators were hired (with USDA financial support) for the initial year at each site to manage the program, with the understanding that subsequent, sustainable state and local funding sources would be developed. Despite early skepticism among growers, pest damage and use both dropped after the first year. Viewing success, surrounding areas wanted to participate. New areas were incorporated into the program on the condition they hire a site coordinator. Throughout the program there was significant reductions in pest damage and total absolute pesticide applications, with shifts to more selective pesticides with lower-risk profiles (Calkins and Faust 2003; Farrar, Baur, and Elliott 2016).

Area-wide Pink Bollworm Control

In October 2018, the USDA declared pink bollworm (*Pectinophora gossypiella*) eradicated in the continental United States.

While theTexas population and bollworm one in Louisiana were eradicated in 1919, pink bollworm appeared in Arizona by 1926. The pest reinvaded Texas' Lower Rio Grande Valley in 1936, spreading to Louisiana, Arkansas, Oklahoma, and New Mexico.

In October 2018, the USDA declared pink bollworm (*Pectinophora gossypiella*) eradicated in the continental United States (USDA 2018). Pink bollworm was first reported in the United States in Texas in 1917, and traced to cottonseed shipments from Mexico (Henneberry and Naranjo 1998). While this Texas population and one in Louisiana were eradicated in 1919, pink bollworm appeared in Arizona by 1926. The pest reinvaded Texas' Lower Rio Grande Valley in 1936, spreading to Louisiana, Arkansas, Oklahoma, and New Mexico. An areawide suppression effort in Arizona involving cooperation between federal and state agencies and private industry was initially effective, but discontinued in 1963.

From 1966 to 1980, Losses from pink bollworm in California's Imperial Valley ranged from 8% to 79% of the crop value.

Pink bollworms became re-established in Arizona, spreading to Southern California by 1965 (Henneberry and Naranjo 1998). Pink bollworm control focusing on attacking localized pest populations on a farm-by-farm basis simply through insecticide control proved ineffective (Allen et al. 2005; Henneberry 2007; Henneberry and Naranjo 1998). Because pink bollworm moths are highly mobile, they counter localized control efforts by dispersing over wide areas. Heavy reliance on chemical control led to the evolution of resistance in pink bollworm to chlorinated hydrocarbons and tolerance to synthetic pyrethroids (Henneberry and Naranjo 1998). There were also reductions in natural enemies and increases in damage by secondary pests. From 1966 to 1980, Losses from pink bollworm in California's Imperial Valley ranged from 8% to 79% of the crop value (Burrows et al. 1982).

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In contrast to ineffective control of the farm-by-farm approach, areawide control using diverse tactics proved highly effective in California's San Joaquin Valley (Henneberry and Naranjo 1998). Growers there in 1968 initiated (and substantially funded) a program to prevent pink bollworms from being established in the area. This included (a) use of gossyplure—the pink bollworm sex pheromone—for mating disruption and in gossyplure-baited traps to monitor pest populations and in-migrations, (b) sterile moth releases, and (c) cotton plant destruction and plow down to maintain a 90-day host free period (Henneberry 1994). Trap-based population monitoring allowed for better targeting of areawide suppression efforts. This program has successfully prevented pink bollworm from being established in the San Joaquin Valley over the last 50 years. Control of pink bollworm via sterile moth release proved less effective in other areas where pest populations had established themselves in greater numbers (Henneberry and Naranjo 1998).

This program has successfully prevented pink bollworm from being established in the San Joaquin Valley over the last 50 years. Control of pink bollworm via sterile moth release proved less effective in other areas where pest populations had established themselves in greater numbers.

The 1990s saw the beginnings of growers coordinating pink bollworm control measures over wider areas. In Southern California, growers agreed to mandatory limits including an earliest planting date, latest date for defoliant or plant growth regulator application (before harvest), and latest cotton stalk destruction and field plow down (Chu et al. 1996). These mandatory limits, which shifted cotton production from full to shorter-season management, were combined with gossyplure-baited traps for monitoring as well as biological, chemical, and cultural tactics. USDA and Cooperative Extension professionals monitored project performance as well as pink bollworm populations to track in-migration from outlying areas. In Pima County, Arizona, growers—working together in conjunction with Cooperative Extension and the USDA—also moved toward community-based pink bollworm control (Moore et al. 1992; Thacker et al. 1994). Here too, the project emphasized that growers synchronize their control efforts. Planning involved regular meetings that included growers, Extension faculty, and PCAs, to get grower consensus on a uniform, optimal planting time and scheduling of other control measures. Coordinating the timing of control efforts relied on data from a weather station system maintained by Cooperative Extension. Although a voluntary program, peer pressure influenced grower participation and coordination (Thacker et al. 1994). Some project activities were financed in part by monetary assessments growers imposed on themselves. These California and Arizona community-based programs showed some promising success in reducing both pink bollworm damage and insecticide applications.

In Southern California, growers agreed to mandatory limits including an earliest planting date, latest date for defoliant or plant growth regulator application (before harvest), and latest cotton stalk destruction and field plow down.

Bt cotton is especially effective at controlling pink bollworm. The evolution of resistance to Bt Cry proteins, however, threatens the sustainability of these pest control benefits. There have been 19 documented instances of practical pest resistance to different Bt Cry proteins, with nine instances in the United States (eight in corn, one in cotton, and one affecting both) (Tabashnik and Carrière 2019). Resistance of pink bollworm to Bt cotton in India has been especially problematic (Tabashnik and Carrière 2019).

Bt cotton is especially effective at controlling pink bollworm.

In the United States, resistance of pink bollworm to Bt cotton has not only been avoided, but Bt cotton has been a critical component in the successful pink bollworm eradication program. First commercially available in 1996, Bt cotton was adopted quickly in Arizona, accounting for about two-thirds of Arizona cotton acreage by 1997 and about three-quarters by 2003 (Naranjo and Ellsworth 2010). With Bt cotton, both pink bollworm populations and pesticide applications to control them reached historic lows. Annual sprays to control pink bollworms fell from an average of 2.7 per year from 1990 to 1995 down to 0.64 from 1996 to 2005 (Naranjo and Ellsworth 2010; Tabashnik et al. 2012). Bt cotton was similarly effective on pink bollworm in Southern California (Chu et al. 2006) and Mexico (Traxler et al. 2002).

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To avert the evolution of pest resistance to Bt cotton, the EPA required that growers plant acres of non-Bt cotton refuges near Bt cotton fields. The concept was that a small number of resistant pests surviving on Bt fields would mate with more-abundant susceptible pests from the refuge acres. Because resistance is a recessive trait, larvae arising from such mating would not survive on Bt cotton. Initially, laboratory samples suggested that pink bollworm had the capacity to develop resistance to Bt cotton rapidly. In response, an Arizona Bt Cotton Working Group was formed, which included scientists from the USDA, the Arizona Department of Agriculture, the University of Arizona, the Arizona Cotton Research and Protection Council (ACRPC), and representatives from the Arizona Cotton Growers Association, and Monsanto (Carrière et al. 2001).

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The ACRPC itself was established in 1984 by an act of the Arizona State Legislature, initially to control boll weevil (Neal and Antilla 2001). The law gave the council (Arizona cotton growers appointed by the Governor) authority to levy fees on growers up to $1 per bale, collected during ginning. The Southwest Boll Weevil Eradication Program (SWBWEP) was launched in 1985, which included the ACRPC, the USDA-APHIS, the Arizona Department of Agriculture, the California Department of Food and Agriculture, and Sanidad Mexico. Thus, a grower-led, state-legislated program had been established for area-wide (and even bi-national) pest control well before the arrival of Bt cotton.

Pink bollworm susceptibility was retained from 1997 to 2005, in large part, because growers complied with the refuge strategy. Bt cotton led to areawide suppression of pink bollworm populations, resulting in reduced insecticide applications.

The Bt Cotton Working Group made recommendations to both the EPA and to Arizona cotton growers regarding desired configurations and distance requirements for Bt cotton refuges (Carrière et al. 2001). The Group also developed a remedial action plan to respond to any occurrence of pink bollworm resistance to Bt cotton. The plan included potential restrictions on planting of Bt cotton in areas surrounding a resistant population. Monitoring of the size, spatial distribution, and susceptibility of pink bollworm larvae to the Bt protein were also critical activities. Pink bollworm susceptibility was retained from 1997 to 2005, in large part, because growers complied with the refuge strategy. Bt cotton led to areawide suppression of pink bollworm populations, resulting in reduced insecticide applications (Carrière et al. 2003; Naranjo and Ellsworth 2010).

Eradication involved a combination of mating disruption, cultural practices, crop residue destruction, water management, planting date restrictions, sterile moth releases, and increased planting of Bt cotton.

This areawide suppression made possible a pink bollworm eradication program. Initiated in West Texas, South Central New Mexico, and Chihuahua, Mexico in 2001–2002, eradication involved a combination of mating disruption, cultural practices, crop residue destruction, water management, planting date restrictions, sterile moth releases, and increased planting of Bt cotton (Allen et al. 2005; Staten et al. 2008). This binational program was funded by both cotton growers and the USDA. Entomological research and computer simulations suggested that sterile moth releases could substitute for refuges as a means of preventing resistance (Tabashnik 2011; Tabashnik et al. 2010, 2012). The EPA convened a Scientific Advisory Panel to review the scientific evidence (USEPA 2006) and ultimately approved the Panel's recommendation to allow cotton growers to plant up to 100% of their cotton acreage to Bt varieties. Entomological research and computer simulations suggested that pink bollworm sterile male releases in addition to crop habitat utilization by cotton bollworm minimized the value of refuges for preventing resistance to Bt cotton (Antilla and Liesner 2008; Grefenstette, El-Lissy, Staten 2009; Head et al. 2010; Tabashnik et al. 2010).The eradication program expanded east to west over time (Allen et al. 2005; El Lissy 2003; Grefenstette, El-Lissy, Staten 2009; Staten et al. 2008). In 2004, Arizona growers approved participation in the programs (Antilla and Liesner 2008). Passage required approval of two-thirds of growers, who represented at least half of Arizona cotton acreage (AZ Rev Stat § 3-1086.02). The program involved collaboration between the USDA and University of Arizona scientists, Cooperative Extension, the ACRPC, and the National Cotton Council as well as counterparts in other U.S. states and in northern Mexico (Anderson et al. 2019; Antilla and Liesner, 2008; Grefenstette, El-Lissy, Staten 2009).

With the constraints of refuge requirements removed, Bt cotton rose to 98% of total cotton acreage by 2008 (Naranjo and Ellsworth 2010). In Arizona, pesticide sprays for pink bollworm plunged and ceased altogether by 2008 (Naranjo and Ellsworth 2010). Annual monitoring in Arizona detected no pink bollworm larvae in cotton bolls from 2010 to 2018 and no wild pink bollworm moths in the field from 2013 to 2018 (Liesner, Fairchild, and Brengle 2019; Tabashnik and Carrière 2019).

Keys to Success

The area-wide control of both codling moth and pink bollworm share several keys to success.

1. The pests were controlled using a diverse array of chemical and nonchemical tactics. No single product or practice was responsible for success. The introduction of Bt cotton did change the pest dynamics in the Southwest United States, but Bt cotton—rather than being a "silver bullet"—may be better thought of as one important arrow in a quiver. Both "hard technologies" (improved seeds, traits, chemicals) and "soft technologies" (knowledge-based cultural management tactics such as sampling, thresholds, and group timing of planting and crop destruction) were critical for success (Reisig, Ellsworth, and Hodgson 2019).

2. While chemical-based strategies implemented at the farm level proved ineffective, diverse tactics were employed in a socially organized, collective fashion relying on multiple decision-making bodies, operating across vertical and horizontal networks. There was extensive collaboration between private technology suppliers, growers, state agencies,

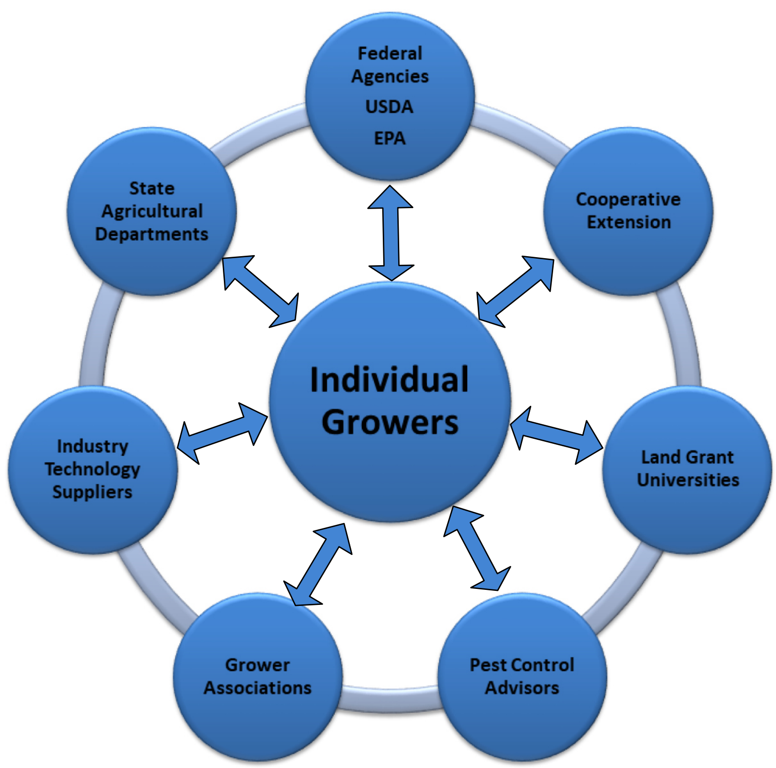

Figure 1. Network of decision makers in successful pest management.

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and federal agencies (Figure 1). Growers were actively engaged in all aspects including decision-making, program financing, program implementation, and enforcement of rules in mandatory systems and peer pressure for voluntary systems. This created a new social construct for pest management.

3. Both programs relied on incrementalism. Programs expanded in terms of geography and complexity, but built on more modest localized successes. Initial successes felt by actual growers encouraged further practice adoption. Public sector support through direct USDA funding and through support for land grant universities and Cooperative extension were important. There were strong scientific foundations underlying the deployment of new strategies. This was important not only for increasing grower confidence, but also for getting buy-in by the EPA. Research professionals were instrumental in implementing constant program monitoring and information sharing.

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Stewardship Programs: Recommendations

The increasing productivity of U.S. agriculture and declining real price of food and fiber suggest that pest management has been effective.

The increasing productivity of U.S. agriculture and declining real price of food and fiber suggest that pest management has been effective (Gaffney et al 2019). However, such aggregate performance measures hide the specific contributions of pest control, as weather, management, capital, technology and other factors combine to influence productivity. Perhaps more importantly, the measures are backward looking and do not reveal the adequacy of stewardship policies for future pest management technologies. Indeed, comprehensive assessments of the sustainability of GM crop pest management approaches suggest that the stewardship of future breakthrough technologies is by no means assured (NRC 2010a; NRC 2016; EPA 2018). Responding to that challenge, we recommend five actions to improve the stewardship of pest management technologies in agriculture.

Recommendations:

1. ***Engage inclusive stakeholder groups to inform the stewardship program***

A crucial first step in developing an effective stewardship program is to identify the stakeholder groups who have legitimate interests in the outcome.

Promoting effective stewardship of pest management technologies boils down to managing a valuable ecosystem service—the susceptibility of pests to control by chemical and non-chemical treatments (Ervin et al. 2019). The development of resistance diminishes the stock of susceptibility and the flow of that service (Jorgensen et al. 2018). A crucial first step in developing an effective stewardship program is to identify the stakeholder groups who have legitimate interests in the outcome. Affected parties from the local area, region and beyond can help identify ecosystem attributes, effects and benefits that matter, and why they matter. A central challenge is identifying all parties with legitimate interests. Use of this public engagement must balance an ability to represent multiple interests with administrative costs and time requirements. An important benefit of the engagement of all stakeholders is the integration of local knowledge of ecosystem conditions with available science.

Scientific studies have documented the importance of gaining stakeholder input to inform environmental programs (e.g., Haddaway et al. 2017). For example, stakeholder engagement is crucial to frame the management context and tailor inputs to local needs and data availability (Ruckelshaus et al. 2015). Note that if stakeholders include anyone who has an interest in the (resource management) process or outcome, then service users and government agency staff responsible for managing the resource should participate (Haddaway et al. 2017). Appropriate engagement assures knowledge production processes that are credible, relevant and legitimate (Cash et al. 2003; Cowling et al. 2008). Comprehensive engagement is critical as it helps build trust among the parties and construct a full picture of the values in play and the tradeoffs including ecological and cultural perspectives (Iniesta-Arandia et al. 2014, Sapp et al 2009).

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A list of possible stakeholders in pest management technologies includes:

- Individual users, e.g., farmers and their managers and farm laborers
- Pest control technology manufacturers
- Independent pest consultants and agricultural retailers who provide pest management products and services, e.g., production advice
- Government agencies that have oversight or assistance roles with pest management technologies, e.g., the USDA, EPA OPP and DOI agencies managing public lands.
- University extension, the USDA, State Departments of Agriculture, and research personnel who provide pest management assistance
- Non-governmental organizations involved in IPM, food and natural resource management
- Consumers of food, fiber and bioenergy products

Reflecting the heterogeneity of crop production situations, the composition of relevant stakeholders is not generalizable and will vary by region according to production, environmental and socio-economic conditions.

2. Develop improved research capacity that identifies the incentives, risks and constraints that influence effective stewardship of pest management technologies

The 2010 NRC panel on the effects of GM crops on farm sustainability in the United States made this recommendation after their assessment:

"*Recommendation* 3. *Public and private research institutions should allocate sufficient resources to monitor and assess the substantial environmental, economic, and social effects of current and emerging agricultural biotechnology on U.S. farms so that technology developers, policy makers, and farmers can make decisions that ensure genetic engineering is a technology that contributes to sustainable agriculture* (NRC 2010)."

This recommendation derives from the panel's finding that research on the implementation of GM crop technologies had not kept pace with the widespread adoption of the crops. In particular, interdisciplinary-based empirical research on the environmental and socio-economic effects, including changes in pest management regimes, of those adoption patterns was found deficient.

Research on the implementation of GM crop technologies had not kept pace with the widespread adoption of the crops. In particular, interdisciplinary-based empirical research on the environmental and socio-economic effects, including changes in pest management regimes, of those adoption patterns was found deficient.

More recent assessments indicate this lack of credible information on GM crop pest control technologies persists (EPA 2018; NRC 2016). Without improved research on the impacts on various stakeholder groups over time, developing effective stewardship programs will be fraught with uncertainty.

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The enhanced research capacity should be undertaken as public-private collaborations for two foundational reasons. First, the impacts of pest management technologies are both private and public in character. Private effects include the efficacy and cost of products used on private lands. Public or social effects include the impacts on parties away from the lands to which they are applied. Examples of such externalities include changes in erosion that degrade downstream water quality and detrimental effects on crops on neighboring lands due to pesticide drift. Privately sponsored research can address many of the private effects but is generally insufficient in monitoring off-site impacts. Given the growing body of evidence that documents the mobility of herbicide-resistant weeds across farm boundaries, the need for public research is evident (Beckie et al. 2015; Ervin and Frisvold 2016; Shaner and Beckie 2014). Such public research by universities and government can play a complementary role to private research by providing basic and public science (Ervin, Glenna, and Jussaume 2011). The specific nature of the public-private collaboration will depend on the biophysical conditions of the pest situation and the socio-economic conditions of the communities that are collaborating to innovate improved stewardship. For example, in some situations, it may be about collaboration mainly between firms and government agencies. For others, it may involve participatory based research that incorporates a range of stakeholders, including growers, ag chemical suppliers, government agencies, independent production advisers, farm labor, conservation and environmental groups and others. The latter type of broad composition may be necessary for pest stewardship issues that transcend local areas into regions.

The specific nature of the public-private collaboration will depend on the biophysical conditions of the pest situation and the socio-economic conditions of the communities that are collaborating to innovate improved stewardship.

3. Build human management skills associated with pest technology stewardship

Implementing smart and flexible policies for agriculture tailored to local environmental, social and economic conditions will require high levels of producer and human management skills (Batie and Ervin 1999). Improving the stewardship of pest management technologies is full of complex human and natural system interactions and therefore emblematic of this requirement. Just producing improved research information on pest population dynamics, landscape effects, and treatment options will not assure effective use. The contributions in this report on the benefits, risks and barriers to implementing effective stewardship programs articulate the complexities of the task. Given the uncertainties replete in this complex challenge (Shaw 2016), high levels of management capacity on the part of producers, industries advising them and government agency staff are necessary. A specific pest management conundrum exemplifies this need. Pest management scientists, manufacturers, crop advisers, and government agency staff all recognize the need to rotate tactics and pesticide modes of action to control the evolution of resistance. Yet, the adoption of multiple tactics and modes of action as a stewardship practice to deter resistance buildup remains relatively low (Peterson et al. 2018). The task of building management capacity for improved pest management technology stewardship will likely be shared among all facets of industry involved in pest man-

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agement, academe, government and non-governmental organizations, such as commodity associations. However, that sharing of responsibility will require careful coordination to minimize duplication and assure consistent messages are delivered. The choice of a leadership organization to catalyze this critical effort is an early priority and will depend on the specific pest control challenge and the relevant socio-economic conditions, including trust relationships, in the region.

4. Promote voluntary community-based stewardship for pest management technologies

Recent survey data indicate that the U.S. agriculture industry wishes to avoid more government regulation in addressing pesticide resistance and stewardship (Schroeder et al. 2018). At the same time, new research documents that a clear majority of farmers disagree that herbicide-resistant weeds can be managed effectively without cooperation amongst growers in a community (Ervin et al. 2018). These twin findings suggest that effective pesticide management stewardship must likely emanate from collaborative community-based efforts. Science has documented multiple successful collaborative efforts to manage such common property or “common pool” resources in different countries (Ostrom 2009). However, the requirements to actualize these community-based efforts are multiple and daunting (Ervin and Frisvold 2016). Adding to the challenge, the mobility of weeds, insects and diseases across ownership boundaries implies that managers of non-agricultural lands, such as highways and other public lands, must also be engaged as the issues overlap.

Nonetheless, examples in collaborative insect management, including the codling moth and pink bollworm control cases discussed above, suggest it is feasible if the right ingredients are in place. Importantly, those successes were achieved with multiple layered (polycentric) governance regimes in which producers, federal and state government, industry, non-governmental organizations and academia played different but essential roles. It seems very likely that similar coalitions of actors and organizations will need to collaborate in improved pesticide stewardship programs.

5. Reform public and private policies that work against effective stewardship

Innovative stewardship programs with robust stakeholder input, improved research on pest management technologies and increased management capacity, all used in community-based efforts, will not reach their potential if private and public policies discourage effective pest management technology stewardship. Examples of such policy conflicts abound. Government crop yield insurance programs may hide yield decreases due to resistance buildup that could incentivize farmers to take proactive stewardship action to lessen further decreases. Government programs may impact the choice of growers to use tillage for weed control in situations where the on-site and off-site erosion effects cause significant damages. Pesticide industry programs that promote recurring use of pesticides with the same modes of action, such as early order discounts, diminish the effectiveness of those compounds. Uniform pesticide regulations, such as labeling restrictions, can diminish flexibility by growers in certain regions to alternate safe pesticide compounds. The potential for these conflicts in

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pursuing pest management technology stewardship is perceived by farmers (Schroeder et al 2018). Inventorying the real conflicts that impede the implementation of progressive pesticide stewardship actions is a high priority.

Innovative stewardship programs for new pest management technologies must address all four components of sustainable agriculture and engage growers and all relevant stakeholder groups from the outset.

Conclusions

Current efforts to conserve and enhance hard and soft pest management options to address escalating environmental and socioeconomic challenges are inadequate. Innovative stewardship programs for new pest management technologies must address all four components of sustainable agriculture and engage growers and all relevant stakeholder groups from the outset. Improved interdisciplinary research and management capacities in the public and private sectors will be key in this process of innovation. Community-based collaborations hold considerable promise in addressing the wicked pest management challenge. Ameliorating public and private policy conflicts with responsible stewardship objectives will aid their efforts. Finding champion leaders and giving them the time and resources to build diverse coalitions and persevere through uncertain environmental, technology, and socioeconomic conditions are essential steps forward.

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