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Shock and Awe Pest Management: Time for Change

Terrance M. Hurley
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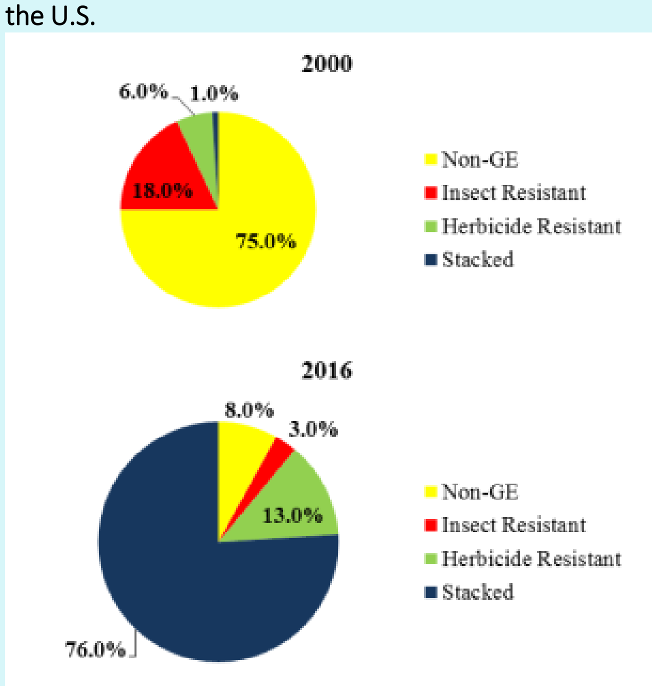
Genetically engineered *Bacillus thuringiensis* (Bt) corn and Roundup Ready soybean were made commercially available in the United States in 1996. Nearly two decades later it is now evident how this new technology disrupted developments in Integrated Pest Management (IPM) and precision agriculture with something that increasingly looks like what IPM and precision agriculture were conceived to replace—one-size-fits-all, prophylactic crop management. This one-size-fits-all approach inextricably links insect, weed, and disease management decisions, making it increasingly difficult to address herbicide resistant weed problems without also addressing the broader crop protection concerns and challenges facing corn and soybean farmers.

Shock and Awe Pest Management

The U.S. Department of Agriculture's National Agricultural Statistics Service (USDA-NASS) started tracking genetically engineered crops in 1996. By 2000, three classifications were developed for reporting levels of genetically engineered corn adoption: Insect Resistant, Herbicide Resistant, and Stacked with both insect and herbicide resistance. Figure 1 shows the remarkable reversal of fortune from 75% non-genetically engineered and 1% stacked-genetically engineered corn in 2000 to 8% non-genetically engineered and 76% stacked-genetically engineered corn in 2016. Impressive as this trend is it is far from a complete story because these three classifications are now too coarse.

Figure 1: Percentage of Non- Genetically Engineered (Non-GE) and Genetically Engineered Insect Resistant, Herbicide Resistant, and Stacked Corn Varieties in the U.S.



Source: USDA-NASS, 2001-2016

The first varieties of Bt corn were engineered to produce a single protein that is toxic to the European corn borer, one of the most challenging corn pests in 1996. This built a highly effective pesticide directly into the corn plant. The first varieties of herbicide tolerant soybean were engineered to withstand glyphosate herbicide giving farmers a new, inexpensive, and effective option for managing a range of weeds that commonly challenge soybean production. By 2000, when USDA-NASS began reporting levels of GE corn in their annual June crop acreage reports, genetically engineered herbicide tolerance was showing up in "stacked" Bt corn. New Bt proteins for managing corn rootworm made their way to market in 2003, with new proteins for managing European corn borer also emerging. Soon to follow was the "pyramiding" of multiple Bt proteins for managing European corn borer and multiple Bt proteins for managing corn rootworm.

In 2016, Monsanto's top-shelf Genuity SmartStax corn included three proteins to control above ground pests such as the European corn borer, two proteins to control corn rootworm, and tolerance to two herbicides (Table 1). Dupont/Pioneer's Optimum AcreMax Xtreme corn was similarly well protected as was Syngenta's Agrisure Duracade 5222 E-Z Refuge corn. But the protection did not stop there as this corn seed also came coated with one or more pesticides. Examples include Bayer's Poncho/Votivo seed treatment with a neonicotinoid insecticide and nematicide, Monsanto's Acceleron seed treatment with a neonicotinoid insecticide and three different fungicides, and Syngenta's Avita Complete Corn 500 seed treatment with a neonicotinoid insecticide, nematicide, and four fungicides. With such comprehensive and overwhelming force brought to bear on important pest threats to U.S. corn production, Shock and Awe Pest Management (SAPM) seems like an apt description.

Table 1: Examples of Genetically Engineered Corn Seed Brands with Bt and Herbicide Tolerant Traits, and Insects Controlled or Suppressed

Company	Brand Name	Bt Proteins	Herbicide Tolerance	Insects Controlled or Suppressed
DuPont/ Pioneer	Optimum AcreMax Xtreme	Cry1F	Glyphosate	Black Cutworm
		Cry1Ab	Glufosinate	Corn Earworm
		mCry3A		European Corn Borer
		Cry34/35Ab1		Fall Armyworm
				Stalk Borer
				Southern Corn Borer
				Western Bean Cutworm
				Corn Rootworm
Monsanto	Genuity SmartStax	Cry1A.105	Glyphosate	Black Cutworm
		Cry2Ab2	Glufosinate	Corn Earworm
		Cry1F		European Corn Borer
		Cry3Bb1		Fall Armyworm
		Cry34/35Ab1		Stalk Borer
				Southern Corn Borer
				Western Bean Cutworm
				Corn Rootworm
Syngenta	Agrisure Duracade 5222 E-Z Refuge	Cry1Ab	Glyphosate	Black Cutworm
		Cry1F		Corn Earworm
		Vip3A		European Corn Borer
		mCry3A		Fall Armyworm
		eCry3.1Ab		Stalk Borer
				Southern Corn Borer
				True Armyworm
				Western Bean Cutworm
				Corn Rootworm

Source: Adapted from DiFonzo (2016)

While U.S. soybean farmers have access to seed that is tolerant to multiple herbicides and coated with one or more pesticides, soybean with Bt proteins were not commercially available in the United States in 2016—they were commercially available in South America. With several companies having U.S. Environmental Protection Agency (EPA) approval for soybean with multiple Bt proteins, it seems likely that the U.S. soybean crop may soon have a level of protection that rivals corn.

SAPM Versus Integrated Pest Management

Integrated pest management (IPM) began to receive attention in the 1970s as the adverse consequences of repeated and widespread pesticide use emerged. These consequences included the evolution of pest resistance, which decreases a pesticide's effectiveness. They also included environmental concerns such as diminished water quality and wildlife abundance as well as human health concerns. To mitigate these adverse consequences, a basic tenet of IPM is more selective pesticide use. For example, more selective use may come from farmers scouting for pests and only applying pesticides when an infestation is likely to cause an economically significant loss—a loss in crop value in excess of treatment costs. More selective use also implies choosing pesticides that only control the problem pest, rather than a broad range of different pests, which avoids collateral damage to beneficial insects and other wildlife.

Another important tenet of IPM is the use of multiple pest management tactics including cultural, biological, and mechanical management practices in addition to pesticides. Examples of cultural practices are crop rotation and varying planting dates. An example of biological management is the release of beneficial predatory insects. Examples of mechanical control include tillage and weed seed destruction.

More generally, IPM can be framed within the precision agriculture paradigm, which is often summarized by three *R*s—using crop inputs in the *Right* amount at the *Right* time, and in the *Right* place. The use of IPM is promoted by the EPA in many of its public statements and official rule making because it considers IPM an environmentally friendly pest management approach.

U.S. corn farmers can now get a nearly complete pest management program with their seed order when using SAPM. This program effectively commits the farmer to a simple strategy of treating almost every planted acre with a suite of pesticides regardless of whether the targeted pests are likely to result in economically significant losses. Additionally, many of the pesticides it deploys are systemic, meaning they provide protection for extended periods of time and, in some cases, the entire cropping season. This treatment without first scouting for evidence of losses over extended periods of time raises questions about SAPM's compatibility with IPM specifically and precision agriculture more generally.

When the best corn or soybean varieties for a farmer's fields are only available with glyphosate tolerance, results from behavioral economics make it unsurprising that some farmers will use glyphosate even if they prefer another herbicide. They will use glyphosate instead of their preferred herbicide because they have already incurred the added expense of buying glyphosate resistance crop seed—they fail to ignore sunk costs. This sentiment was shared by David Miller, an Iowa farmer, at the National Academy of Science's 2012 *National Summit on Strategies to Manage Herbicide-Resistant Weeds*. Additionally, with glyphosate tolerant corn and soybeans, farmers can quickly move between treating corn and soybean fields for weeds without having to worry about stopping to clean out or change equipment. These and other unanticipated responses to the introduction of glyphosate tolerant crops contributed to widespread and exclusive reliance on glyphosate by many farmers—a practice that is contrary to IPM's multiple tactics principle.

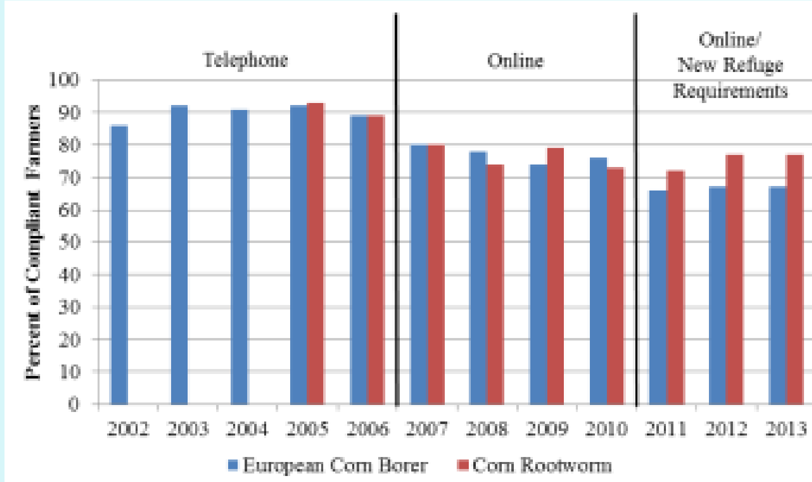
Even though facets of SAPM are incompatible with IPM, it has also been viewed favorably by the EPA because it considers many of the pesticides used by SAPM to be reduced risk—safer for human health and the environment than the pesticides being replaced. Still, as glyphosate resistant weeds have become increasingly problematic, the seed and chemical industry has responded by encouraging farmers to use more residual herbicides, and developing crops with tolerances to dicamba and 2-4 D—herbicides the reduced risk glyphosate was meant to replace.

SAPM Benefits

Regardless of its compatibility with IPM and precision agriculture, SAPM offers a range of benefits to farmers, and seed and chemical suppliers. It can reduce seed production, distribution, and inventory costs by making it possible to meet farmers' crop protection needs with a one-size-fits-all product that is conveniently packaged into the seed. Seed companies are continually adapting the agronomic traits of corn and soybean to better match variation across the landscape in soils and climate, resulting in regionally adapted varieties. While it is also possible for companies to adapt their genetically engineered crop protection traits to better match variation in pest problems across the landscape, the cost of offering a complete suite of crop protection traits instead is negligible. Once seed is successfully transformed to include genetically engineered crop protection traits, scaling up is just a matter of seed replication regardless of whether there is a single trait or bundle of many traits.

SAPM has made it possible for seed and chemical companies to address regulatory challenges. The EPA requires farmers to plant a proportion of conventional corn—referred to as refuge—in addition to Bt corn in an effort to manage the evolution of insect resistance to Bt. By slowing the evolution of resistance, refuge helps to conserve the effectiveness of Bt for managing insects. As farmer compliance with the EPA's refuge requirements started showing signs of deterioration in the mid-2000s (Figure 2), the companies were able to use the multiple Bt proteins per pest pyramiding principle to secure changes to the regulations that reduced the required proportion of refuge from twenty percent to as low as five percent in the corn belt. With these lower refuge requirements, farmers could protect more of their corn crop with Bt, reducing compliance costs. More importantly, these changes allowed the companies to sell Bt corn seed with the required refuge seed mixed into it in the bag. Since sorting Bt from refuge seed out of the bag is not practical, planting refuge to comply with the EPA requirement is unavoidable.

Figure 2: U.S. Farmer Compliance with European Corn Borer and Corn Rootworm Refuge Size Requirements for Planting Bt Corn



Source: EPA, 2016

Note: The mode for measuring compliance changed from telephone to online survey in 2007. There were also new refuge requirements introduced in 2011.

As the size of farms by acres operated has bifurcated with a growing proportion of smaller farms that rely on off-farm employment for supplemental income and an increasing amount of crop acreage being operated by larger farms trying to maintain income with shrinking margins between crop revenues and production costs, time has become one of the scarcest of farm inputs. With insecticides for the most significant insect pests and tolerance to multiple broad spectrum herbicides built into the seed, SAPM helps reduce the number of field operations, while also making the timing of those operations more flexible and convenient. These attributes are consistently identified as important drivers of pest management decisions beyond profitability (Carpenter and Gianessi, 1999; Fernandez-Cornejo, Hendricks, and Mishra, 2005; Hurley, Mitchell, and Frisvold, 2009a; Hurley and Mitchell, 2016). They give farmers more time and simplify management decisions, particularly when compared to the time demands and complexity of IPM.

SAPM can also benefit farmers in developing countries with limited infrastructure, market access, and education. With insecticides built into seed and the ability of seed to naturally replicate, it is possible to meet a farmer's pest management needs with a single seed delivery rather than with repeated deliveries of bulky seed and chemicals. The farmer's crop is protected once seed is planted, with no need for additional chemical applications or special knowledge. While developing-world applications can potentially improve food security, this potential has not been realized due to political, socio-economic, and other obstacles beyond the scope of this article.

SAPM Challenges and Concerns

In 2007, Paul Mitchell led a team of economists to explore the value of glyphosate tolerant corn, cotton, and soybean to farmers as evidence of glyphosate resistant weeds became indisputable. The results of the team's effort were published in a special issue of *AgBioForum* (Frisvold, Hurley, and Mitchell, 2009; Hurley, Mitchell, and Frisvold, 2009a-c). An expert panel assembled by the National Academy of Science to explore the impact of genetically engineered crops on U.S. farm sustainability concluded in their 2010 report that herbicide resistant weeds were a threat to sustainability (National Research Council, 2010). This report has been followed by a series of national workshops and listening sessions that continue as of the writing of this article. On October 15, 2014, the U.S. Secretary of Agriculture, Tom Vilsack, committed to channeling additional resources into addressing the problem of herbicide resistance—a problem that includes an increase in the number of species of weeds with multiple herbicide resistance. More recently, the National Academy of Science released a 2016 report exploring the broader impacts of genetically engineered crops (NRC, 2016). As before, the report concludes that more research is needed to improve herbicide resistant weed management.

A team of entomologists from Iowa State University led by Aaron Gassman published a 2011 report on their 2009 discovery of western corn rootworm that were resistant to one of the three types of Bt proteins being deployed to control it (Gassman et al., 2011). By 2014, Professor Gassman's team was reporting the discovery of western corn rootworm with cross-resistance to two of the three types of Bt proteins being used to control it (Gassman et al., 2014). Just a year earlier, a team led by Bruce Tabashnik from the University of Arizona published a global review of Bt crops that identified five insect species with resistance to Bt proteins (Tabashnik, Brévault, and Carrière, 2013).

Alternatively, a team of researchers led by William Hutchison at the University of Minnesota published a 2010 report showing how the area-wide suppression of European corn borer due to Bt corn had provided cumulative benefits of nearly $7 billion to non-Bt as well as Bt corn farmers in five Midwestern states (Hutchison et al., 2010). However, with European corn borer populations at historically low levels for more than a decade, the benefits of continuing to deploy Bt proteins to manage these populations seems questionable. This is especially true when considering the future costs of continuing to build Bt resistance in these European corn borer populations while there is currently little, if any, yield loss occurring with area-wide suppression.

The discovery of sub-lethal effects of neonicotinoid insecticides on bee behavior combined with declining bee populations sparked increased regulatory scrutiny by the EPA, Canadian Pest Management Regulatory Agency, and California Environmental Protection Agency in 2013. This increased scrutiny resulted in a 2014 report questioning the economic value to farmers of neonicotinoid seed treatments in soybean production, though my own research with Paul Mitchell finds an average value of around $11-12 per treated acre (Hurley and Mitchell, 2016). It also led to increased restrictions on the use of neonicotinoid insecticides in Ontario, Canada. Pollinator concerns resulted in the Minnesota Governor Mark Dayton's August 26, 2016 Executive Order "requiring the 'verification of need' prior to the use of neonicotinoid pesticides, where appropriate." However, there is some confusion regarding the applicability of this executive order to the neonicotinoid seed treatments that are so extensively used by Minnesota corn and soybean farmers. Also of concern are recent declines in other insect populations, including the charismatic Monarch Butterfly, that have been linked to herbicide tolerant crops, at least circumstantially.

Future of Corn and Soybean Pest Management

It is unreasonable to solely accuse SAPM for reemerging concerns and challenges, but it is also difficult to deny some culpability. Regardless, the heightened sense of concern among farmers, seed and chemical companies, and policy makers provides an opportunity to reassess the economic and biological resilience of our predominant crop pest management strategy in corn and soybean. Resilience is used, rather than sustainability, with purpose. While I am tempted to skip my daily walk on the treadmill, I am aware of the consequences of not exercising regularly. Analogously, evolutionary principles tell us the story of crop pest management cannot end with some notion of sustainability that lets us skip the pesticide treadmill without consequence. Instead, as pests evolve in an effort to thwart our crop defenses—whether chemical, biological, cultural, or mechanical—we must continually bolster those defenses, while preparing for the expected occasional failures and trying to limit collateral damage—a vision of resilience rather than sustainability.

Achieving more resilient pest management requires thought about important tradeoffs. How much effort is devoted to bolstering our defenses versus preparing for them to fail? Under which circumstance is comprehensive management a better option than selective management? What type and how much collateral damage are acceptable? What are the appropriate public and private roles in the development and execution of resilient pest management? To what extent do the answers to these questions differ across geographies, cropping systems, and the socio-economic conditions of our farming communities?

It also requires an understanding of the socio-economics of pest management as well as pest biology. For example, simple, flexible, and time saving as well as profitable management practices are important to farmers, making it unlikely that complex, inflexible, and time consuming management practices will be employed without some incentive—be it a carrot or stick. Some farmers choose not to manage pesticide resistance because the costs of management are immediate and certain, while the benefits come later and are uncertain. Some choose not to manage pesticide resistance because mobile pests can spread resistance throughout a region, which can make a farmer's resistance management efforts futile unless neighbors are also managing resistance.

A more resilient pest management strategy starts with the integration of SAPM with IPM where they are compatible. For example, the deployment of Bt or similar plant-incorporated-protectants can be done more selectively by limiting it to regions where a pest is a consistent problem and removing it from regions where the pest is not—possibly due to area-wide suppression from those same plant-incorporated-protectants. With such a strategy, the type of scouting promoted by IPM transforms into something more akin to the sentinel plot monitoring network managed by the IPM Pest Information Platform for Extension and Education and its companion network the Integrated Pest Information Platform for Extension and Education. The genesis of these networks was the 2004 arrival of soybean rust into the United States. Initial funding sources included various U.S. Department of Agriculture agencies, land-grant universities, and commodity associations. Such platforms can be used to track the regional importance of pests over time and provide guidance for scaling up and deploying more targeted crop protection bundles as needed.

Monitoring efforts need not focus exclusively on pests. The emergence of resistant western corn rootworm coincided with conditions predicted by entomologists such as the continuous planting of Bt corn. By closely monitoring how intensively alternative management tactics are being deployed in a region, it is possible to identify where our defenses are increasingly likely to fail.

The benefits of both types of monitoring are concentrated with farmers, and seed and chemical companies. Therefore, support for these networks can come from these sources through community, commodity, cooperative, and industry work group associations, though some institutional innovation is likely required to make this happen. In addition to securing financial and other resources, this institutional innovation needs to include strategies for managing privacy concerns with the type of information being collected and disseminated. For additional incentives to develop and maintain these networks, the EPA can register and re-register various bundles of crop protection traits more regionally based on a demonstrated need, while offering emergency registrations for unexpected and persistent pest infestations or population resurgences.

The pyramiding of multiple proteins to target a pest is a SAPM principle that aligns with the multiple tactics principle of IPM. While the multiple tactics principle of IPM is usually thought of in the context of combining cultural with chemical practices or mechanical with cultural practices, for example, it also includes the sequential or simultaneous use of pesticides with different biological mechanisms for controlling a pest. This pyramiding could become an EPA norm when registering new Bt or other plant-incorporated-protectants rather than the exception it has been in the past.

Multiple tactics are also important for managing intermittent pest infestations or population resurgences. Here there are opportunities to think beyond the traditional pesticide, cultural, biological, and mechanical tactics to also consider financial tactics. For example, it may be better to indemnify crop losses with insurance rather than try to prevent or mitigate them through the use of pesticides, especially if the losses are rare or time is needed to scale up a more effective area-wide response. The 2014 Farm Bill linked soil conservation programs to farmer eligibility for federal crop insurance financial assistance in effort to encourage participation. Similar changes to future Farm Bills or modifications to crop insurance policies could be used to encourage a more resilient pest management strategy. For example, documented evidence of resistance management could be required for crop insurance financial assistance, or insect, disease, and weed loss coverage due to resistance could be added to policies.

Additional consideration can be given to sustained research into discovering new defenses as well as new ways to deploy existing defenses. There were active research programs on real time weed detection and discrimination for precision weed management in the late 1990s, but this research interest declined rapidly in the United States with the rise of herbicide tolerant crops and sense that weed management problems were solved. This type of research is well-suited to the land-grant university mission and needs to be encouraged and sustained through U.S. Department of Agriculture, National Institute for Food and Agriculture (USDA-NIFA) funding for research and development.

The sense that weed management problems were solved with herbicide tolerant crops offers a convenient transition to some concluding thoughts. A more resilient pest management strategy cannot be achieved without recognizing and avoiding the behavioral tendency toward overconfidence, particularly in light of repeated successes—as was observed with over a decade of use of European corn borer Bt corn and glyphosate tolerant corn and soybean. Overconfidence in our ability to build an impenetrable defense creates complacency. Complacency results in deteriorating regulatory compliance, unrealistic product development time tables, relaxation of regulatory standards, diminished regulatory scrutiny, and the abandonment of efforts to continue to develop promising alternatives. We are then unprepared to respond to inevitable failures in a timely and effective manner without significant collateral damage, which is my perception of where we are now with corn rootworm Bt corn and glyphosate tolerant corn and soybean.

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Author Information

Terrance M. Hurley (tmh@umn.edu) is Austin A. Dowell Professor of Applied Economics, University of Minnesota, St. Paul MN. *Financial support for this research from the Minnesota Agricultural Experiment Station Project Number MIN-14-034, and U.S. Department of Agriculture National Institute for Food and Agriculture Project Numbers 2014-67023-21814 and 2014-68004-21855 is greatly appreciated. All interpretations and any remaining errors are solely the author's.*