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Crop Protection Contributions toward Agricultural Productivity

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ABSTRACT

In much of the world, the percentage of those producing our food has decreased dramatically in the last century—many rely on just a few to provide food and fiber. Much of this productivity comes from crop protection techniques, including synthetic pesticides and fertilizers, but the continued reliance on past methods alone threatens modern-day food security.

The authors of this CAST Issue Paper examine the current plant protection revolution that is driven by the biological realities of pesticide resistance, various market forces, and real or perceived side effects of pesticides. They point out that crop protection chemicals have been “miraculous,” but “their automatic use is no longer efficacious or justifiable.”

Integrated pest management is the preferred approach, and pest prevention is a key component in its success. This paper examines the development of methods used to control disease, insects, and weeds—and the authors stress the need for new technologies and an integrated cropping systems approach.

This science-based review considers many plant protection trends, including the following:

- Disease management and the need for new modes of action
- Insect management and issues involving pesticides
- Weed management and the need for new technologies to control the evolution of resistant weeds
- Biological control of plant pathogens, insects, and weeds—and the need for further research in these areas
- Seed treatment technology—and its various methods and benefits
- Nematicide uses shifting from fumigation and banded row applications to seed treatments

New technologies are becoming important, especially for surveillance and application: (1) drones and other remote-sensing devices lead to more systemic monitoring and methods such as site-specific weed management; (2) “smart sprayers” comprise both detection and chemical spraying systems; and (3) new cultivators have been developed to especially help organic and vegetable crop growers.

Genetic techniques (such as CRISPR-Cas9, RNAi, marker technology, plant-incorporated protectants, and stacked traits) may fit well into integrated systems. Whatever approaches are adopted, however, resistance management plans are essential. A multidisciplinary approach is needed to spur adoption of best management practices—and food producers must consider how to handle economics, regulations, land stewardship, incentives, and new technologies.

The needs are immediate and the challenges formidable. The authors make it clear that “scientists from all the pest management disciplines need to improve communication and work together to develop integrated strategies for managing pests while preserving ecosystem services and farm productivity.”

In order to manage agricultural landscapes’ complex requirements, integrated plant protection technologies must continue to be developed to provide effective, economical, and efficient pest management while preserving crop productivity and ecosystem services. (Photo from igorstevanovic/Shutterstock.)

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INTRODUCTION

For thousands of years, humans have struggled to produce food and lessen the damage inflicted by pests. Early attempts to improve the quantity and quality of crops varied considerably throughout the centuries with limited success. As agriculture has evolved, fewer individuals are farming larger acreages and producing greater yields. Because of this shift in production outputs, 98% of the population in the United States and Canada relies on the remaining 2% to produce the food. This model is not true throughout the world, but the percentage of those producing our food is far less than it was even 100 years ago. To a great extent, this model has been realized because of unprecedented advancements in production technologies, including synthetic chemical pesticides and fertilizers. Unfortunately, our continued reliance on the use of single tactics to address pest issues has resulted in the loss of both chemical and cultural management tools and threatens our food security.

Since the early 1960s, the yield average productivity of wheat, rice, and maize has increased by a factor greater than 2 (Oerke 2006). This increase in productivity has been accompanied by an increase in sales of herbicides, fungicides, and insecticides by 15- to 20-fold, to more than US$30 billion worldwide (Oerke 2006). Although grain production also has doubled over the past 40 to 50 years, partially as a consequence of changes in crop protection, the overall proportion of crop losses has actually increased. Depending on the crop, pests are estimated to be responsible for 25 to 50% or more of global crop losses. Losses are particularly high in poorer regions of the world, where climates are relatively wet and warm, crops are grown nearly all year or without rotation, crop varieties or landraces are susceptible, and crop protection is absent or of low efficacy. Overall, weeds produce the highest potential loss (34%), with losses by animal pests and pathogens at 18 and 16%, respectively (Oerke 2006).

Despite a clear increase in pesticide use, crop losses have not significantly decreased during the past 40 years. Increased crop productivity requires adequate crop protection because an increase in potential yields is often associated with increased vulnerability to damage inflicted by pests. Ineffective crop protection by pesticides because of pest resistance requires renewed agricultural innovation. Concomitantly, enhanced integrated pest management (IPM) adoption requires a better understanding of not only the biology and population dynamics of pests, but also how growers make pest management decisions.

Plant protection is undergoing a revolution not unlike the period during the late 1950s to early 1960s when the widespread use of synthetic chemical pesticides proliferated (Aspelin 2003; Kenaga 1989; Pimentel et al. 1991). This revolution is driven by the biological realities of pesticide resistance developing in target pests; market forces that are beginning to make the development, registration, and use of new pesticides cost prohibitive; and real or perceived side effects of pesticides on nontarget organisms, including humans. Nevertheless, synthetic chemical pesticides have enabled crop production to reach unprecedented levels and they continue to be essential for maintaining consistent high yields in the face of increasing weed, insect, and disease pressure, including from alien invasive species. Plant protection has become simplified, and in most cases reliable, because of these miraculous chemicals; however, their automatic use is no longer efficacious or justifiable.

Integrated pest management is a preferred approach to managing the increased insect, plant pathogen, and weed pest problems growers are experiencing. The cornerstone of IPM is pest prevention, involving actions that exclude pests, create environmental conditions that do not support their establishment, or minimize their impact. A primary goal in an agricultural system is to avoid disease, insect, or weed problems before they decrease the quality or quantity of the commodity being produced. Pest exclusion has now become a more effective IPM tactic because of advanced diagnostics based on rapid pest detection, identification, mitigation, and monitoring. Pests can be kept from establishing by diversifying crop production to disrupt weed life cycles or to create host-free periods for insects and diseases.

Additional tools to prevent pest establishment include planting cover crops to alter habitats, mechanically controlling insects and weeds, managing weed seed banks, conserving and augmenting natural enemies, and applying highly selective pesticides. Prevention of pathogen and weed immigration into a field or new habitat and subsequent spread is a continual effort required by growers or land managers. Planting weed-free crop seed, preventing immigration of new or herbicide-resistant (HR) weeds into fields, and mitigating weed propagule dispersal across fields are among the top weed management practices advocated by the Weed Science Society of America (Norsworthy et al. 2012).

Crop protection includes sanitation practices that significantly lessen the risk of HR weeds occurring in arable land (e.g., Beckie et al. 2008). The widespread dispersal of soilborne plant pathogen also can threaten agricultural production. This is best illustrated by the movement of soybean cyst nematode (SCN) in soybean, which was first found in North Carolina in 1954. It is currently distributed across the majority of the soybean-growing regions of North America because sanitation was not practiced (Byamukama and Tande 2013). Once established, pests must be maintained below action thresholds by using some of the same IPM tactics as those for preventing establishment, discovering new pesticide active ingredients that target the pests and can be used in resistance management, and developing modern genetic methods. Crop protection will increasingly depend on new technologies and IPM strategies, including integrated cropping systems that minimize environmental impacts, protect pollinators and other beneficial organisms, conserve natural resources, and are routinely adopted by growers.

PLANT PROTECTION TRENDS—CURRENT AND FUTURE

Plant Pathogen Management with Fungicides

The development of fungicides to combat plant pathogens dates back to the mid-1600s, and our knowledge of fungicides or antifungal compounds has grown exponentially since that time. There are many modes of action (MOAs) that have been discovered with one to many specific active ingredients within a given chemical class of fungicides. The last group of compounds with a novel MOA was released in 1996 and is now the second-largest group of fungicides, the strobilurins (quinone outside inhibitors) (Morton and Staub 2008). Since that time there have been several releases of new commercial fungicide products, but they are combinations of products previously known or new active compounds from a known MOA. Unfortunately, there is a high reliance on only a few fungicide groups with limited MOAs in primary commodity field crops, including strobilurins, triazoles (demethylation inhibitors), and SDHI (succinate dehydrogenase inhibitor) fungicides. Others are available, but these three fungicide groups make up the vast majority of products used today.

Insect Management with Insecticides

Selectivity is the name of the game when it comes to insecticides, with minimal impacts on nontargets, including beneficial insects (natural enemies and pollinators), mammals and vertebrates, and the environment. Many of the older broad-spectrum products have been replaced with newer and more selective chemistry. Many of these newer (< 20 years old) insecticide products are currently hitting the popular press and news outlets because of the Environmental Protection Agency (EPA) requirement that all registrations be reviewed after 15 years. Therefore, many of the products up for reregistration—including the neonicotinoids, diacylhydrazines, acyl ureas, and others—have been in use for nearly two decades (Sparks 2013).

Newer materials (< 10 years old) include the sulfoximines and diamides (chlorantraniliprole and cyantraniliprole). The newest chemistries (< 5 years old) currently available include isoxazolines, metadiamides, cycloxaprid, mesoionics, new diamides (cylaniliprole and tetraniliprole), pyropenes, flometoquin, and fluhexafon (Sparks and Nauen 2015). Although novel, only a limited set of these new materials represents new IRAC (Insecticide Resistance Action Committee) groups of chemistry (Sparks and Nauen 2015).

Weed Management with Herbicides

No herbicides with a novel MOA have been introduced into the field crop marketplace in more than 30 years (Duke 2012). The introduction of transgenic HR crops in the mid-1990s, however, heralded a new level of weed control simplification and further expansion of conservation tillage and farm size in corn, soybean, cotton, canola, and sugar beet production systems (Owen 2016; Shaw 2016). Currently, glyphosate-resistant (GR) crops account for approximately 85% of transgenic crops grown worldwide, and evolution of GR weeds highlights the urgent need for new technologies and approaches for controlling weeds in large-scale conventional systems (Duke 2012; Shaner and Beckie 2014). In addition, the increase in HR weed populations is leading conventional growers to rely again on tillage and hand labor to control these HR weed populations, a nonsustainable situation.

There is little debate over the urgent need for herbicides with new MOAs to manage the evolution of resistance of weeds to existing herbicides. Duke (2012) states that the economic stimulus to the herbicide industry caused by the evolution of HR (especially GR) weeds may result in one or more new MOA herbicides becoming available in the "not too distant future." This prognosis is based on using multiple approaches (e.g., structure-, fragment-, or target-based design; "omics" methods) to new MOA discovery to optimize success (Duke, Bajsa, and Pan 2013; Lamberth et al. 2013) as well as on the fact that there are known nonutilized target sites for which there are inhibitors that are highly effective at killing plants. Nevertheless, the economics of herbicide discovery continue to be dampened by the ever-increasing cost of getting a new product to market and uncertain potential revenue during the lifetime of the patent due to GR crops, generic herbicides, and of course, propensity of weeds to evolve resistance to a product.

NEW BIOLOGICAL INSECT, DISEASE, AND WEED MANAGEMENT TOOLS

Plant Pathogen and Nematode Biologicals

Biological control of plant pathogens is becoming more important with the current sustainability emphasis for agricultural production. The most recent organism to be released in agricultural production was Clariva© (Syngenta Crop Protection), which contains the SCN endoparasite (*Pasteuria nishizawae*) organism that effectively decreased the nematode numbers in microplot studies (Noel, Atibalentja, and Bauer 2005). All *Pasteuria* spp. are obligate parasites that affect a range of nematode species. *Pasteuria nishizawae* (Pn), is the only species of *Pasteuria* observed to parasitize SCN (Noel, Atibalentja, and Domier 2005; Siddiqui and Mahmood 1999).

For effective biological agents to be developed, there is a need for both basic and long-term applied research to be conducted. Researchers are using new tools, such as metagenomics, to gain greater insight into microbiomes in the current era of big data. The root rhizosphere (root-soil connection) is one area of interest for many researchers and is affected by both the plant root and soil for the rhizosphere community (Berg and Smalla 2009). There is also a need for long-term cropping system studies to be funded. Researchers who evaluate effective controls are often limited to single-year funded projects that are crop specific.

A good example of the effectiveness on long-term cropping studies is in the management of *Rhizoctonia* bar patch in wheat (Schillinger and Paulitz 2014). By running continuous cropping system studies over 14 years, researchers were able to demonstrate the development of suppressive soils that are biologically driven. Once a soil becomes suppressive, the specific organisms responsible can be identified and cropping systems can be modified to favor a more rapid shift. Other developed projects look at large-scale screening or specific organisms to identify a specific antagonist or other activity that suppresses a target pathogen. A more recent evaluation of 465 biological treatments for synergistic relationships concluded that there was a greater risk of antagonism among biocontrol agents than synergism and development should focus on individual organisms (Xu et al. 2011).

Insect Biologicals

Biological control of arthropod pests using invertebrate agents and biopesticides is increasing steadily. The use of commercial invertebrate agents will be more common as additional products become available. Currently, 219 species are produced worldwide and quality control protocols are available for the most important ones (van Lenteren 2003, 2012). The industry has been growing at a rate of about 15 to 20% per year (Bolckmans 1999; van Lenteren 2012), so it probably has exceeded $200 million annually. An up-to-date catalog for North America includes 70 species of beneficial nematodes, mites, and insect predators and parasitoids (LeBeck and Leppla 2015). A broader range of biorational products is listed in the “2015 Directory of Least-Toxic Pest Control Products” (BIRC 2015). Microbial pesticides also are gaining popularity, especially as decreased environmental impact alternatives to conventional synthetic pesticides (Koul 2011; Lacey et al. 2015; Marrone 2007; Olson 2015; Ravensberg 2011).

Development and regulatory approval of a novel synthetic pesticide routinely requires $250 million and nine years compared with a microbial pesticide that typically consumes $10 million and four years for the same process (Olson 2015). If the global pesticide market is approximately $60 billion, biopesticides account for about 5%, with a compounded annual growth rate of 12% (Koivunen et al. 2013). Since 2003, many kinds of chemical pesticides (> 300) have been officially banned in the European Union to restrict residue levels. Investments in research and technology, along with these kinds of regulatory actions, are among the changes needed for continued growth of commercial biological control for arthropod pests. Perhaps of greater importance, however, will be the need to educate growers and pest management advisors as to the optimal ways that new biological control products can be fully implemented and conserved.

Weed Biologicals

Commercial biological products for weed control are desirable and will be adopted by users if they can provide equivalent or better control of weeds than other available products at a similar or lower cost and perhaps if consumers perceive that the biological products carry less hazards to people and the environment (Cross and Polonenko 1996). Powell and Jutsum (1993) concluded that successful biocontrol products will fill commercial niches in which chemicals do not work (e.g., weed resistance) or are not politically acceptable (e.g., urban settings, golf courses), as well as in organic systems. The reality is that very few bioherbicides have been commercialized; production and formulation advancements continue to be the most limiting factors to commercialization (Bailey and Mupondwa 2006). It is widely acknowledged, however, that the inherently restricted weed control spectrum and environment-dependent efficacy also limit commercialization potential. Optimizing the discovery and screening process, including rapid identification of natural products (Kao-Kniffin, Carver, and DiTommaso 2013) and genetic manipulations to enhance efficacy of biocontrol microorganisms (Rector 2008), may aid in the successful commercialization of biologicals or natural products.

SEED TREATMENT TECHNOLOGY BENEFITS

Treatment of seed or soil at planting (either in-furrow or lay-by) has historically targeted soil-dwelling pests. Many of the materials used in these treatments are insoluble in water. The water solubility can be measured by the partition coefficient or log P. Many of the insecticidal products used previously have log P values greater than 1 and therefore are not easily taken up by plants and translocated. Compounds in the neonicotinoid class (IRAC group 4A) are soluble in water and have low log Ps (Table 1). These properties have made it possible to treat the seed and have the pesticide translocated from the roots into the plant shoots and leaves. In this way, the materials used to treat the seed become plant-incorporated protectants (PIPs).

The availability of neonicotinoids has made it possible to treat seed and target insects feeding on roots, stems, and leaves. The neonicotinoid insecticides include several commercially available active ingredients: imidacloprid, acetamiprid, thiamethoxam, clothianidin, and dinotefuran (Table 1); although they all have relatively low log P values, only two compounds have been routinely used as seed treatments—thiamethoxam and clothianidin. Partition coefficients explain why neonicotinoids have been used as PIPs, but the coefficients may not explain why seed treatments have been limited to thiamethoxam and clothianidin. The use of neonicotinoid seed treatments has become essential for corn grown in areas where significant insect pressure occurs, such as the southeastern United States, and for vegetable production in California.

New formulation technologies will also impact seed treatment technologies and the ability for materials to be translocated throughout the plant. These advances will allow additional chemistries to be used as PIPs where the products are applied to seed. For instance, anthranilic diamide insecticides have log Ps that are greater than 2, but formulation and nanoparticle technology have been developed to effectively decrease log P, thereby making these compounds translocatable to above-ground plant parts when used as a seed treatment (Wilson 2012).

Corn, cotton, and soybean contribute significantly to the overall production acreage treated with neonicotinoid seed treatments. From 2008 to 2012, neonicotinoid seed treatments were used on an average of 30% of the 28.75 million hectares (ha) (71 million acres) of soybean with a trend of increasing use during the five years of the study (Myers et al. 2014). By 2013, approximately 75% of soybean seeds were treated usually with both a fungicide and an insecticide. Neonicotinoid treatment of field corn seed is routine in parts of the United States where insect pressure is high, but usage in low-to-moderate pest pressure situations indicates that seed treatment use and need do not necessarily correlate. In cotton production, between 2.43 and 3.65 million ha (6 and 9 million acres) are treated (Table 2), and thrips are the primary target for cotton seed treatments.

For vegetable production in California, between 162,000 and 283,000 ha (400,140 and 699,010 acres) are planted with neonicotinoid-treated seed, primarily thiamethoxam (Table 3). The clothianidin treatment is restricted to sweet corn seed, and annual acreage is limited to less than 500 ha (1,235 acres) in California. In soybean, the utility of the seed treatments has been questioned (Myers et al. 2014), although the treatments were believed to be effective on several homopteran and coleopteran insect pests. Field corn in some regions of the United States also routinely receives insecticide seed treatments to combat chinch bugs and soil-dwelling insects. In California, seed treatments are routine (Table 3), and the targets for these treatments for vegetable production include aphids, thrips and whiteflies, cutworms and armyworms, flea beetles and bean leaf beetles, and leaf hoppers and chinch bugs. In the Pacific Northwest, nearly 100% of the sugar beet seed is planted with a neonicotinoid seed treatment to prevent beet leafhopper and curly top virus problems. The seed treatment is used throughout because it is an effective management tool to supplement

Table 1. Partition coefficients (commonly referred to as log P) for different IRAC groupings

IRAC Category	Category Name	Chemical Name	Log P*
4A	Neonicotinoid	Acetamiprid	0.8
4A	Neonicotinoid	Clothianidin	0.7
4A	Neonicotinoid	Imidacloprid	0.6
4A	Neonicotinoid	Thiamethoxam	-0.1
4A	Neonicotinoid	Dinotefuran	-0.6
1B	Organophosphate	Acephate	-0.85
9C	Flonicamid	Flonicamid	0.3
28	Diamides	Chlorantraniliprole	2.86
28	Diamides	Cyantraniliprole	1.91
28	Diamides	Flubendiamide	4.98

* The log P is a ratio of the concentration of one compound in two immiscible liquids at equilibrium; the lower the value of log P, the lower the hydrophobicity.

Table 2. The use of seed treatments in cotton throughout the United States and costs associated with the treatments (Williams 2010, 2011, 2012, 2013, 2014, 2015)

Year	Hectares/Acres Treated	Cost Range ($/acre)
2015	2,671,276/6,678,189	7.13–16.20
2014	3,594,364/8,985,912	7.00–15.88
2013	2,525,875/6,314,687	7.00–21.25
2012	3,804,356/9,510,890	7.00–16.32
2011	3,085,485/7,713,713	3.00–16.32
2010	2,473,874/6,184,685	4.50–15.00

Table 3. The use of thiamethoxam (Cruiser®) seed treatments on vegetable crops in California—results from a query of the California pesticide use reports (California Department of Pesticide Regulation 2013)

Year	Hectares/Acres Treated	Crop
2013	289,640/724,100	Squash, cucumbers, beans, onions, peas, melons, lettuce
2012	163,710/409,275	Squash, cucumbers, beans, onions, peas, melons, lettuce
2011	256,990/642,475	Squash, cucumbers, beans, onions, peas, melons, lettuce
2010	201,000/502,500	Squash, cucumbers, beans, onions, peas, melons, lettuce

host plant resistance (Strausbaugh, Wenninger, and Eujayl 2012).

NEMATICIDE SEED TREATMENTS

The general use of nematicides has shifted from applications applied as fumigants or banded row applications to seed treatments as a means of decreasing exposure to applicators and the environment. Because nematodes are "worm like animals," most nematicides have high toxicities to humans and this has been a very important concern in the industry. Seed treatments also limit exposure to the nematode population (Faske and Starr 2007) and significantly lessen potential environmental effects because of very low doses being positioned where the active ingredient is needed with minimal effect released to the environment.

The SCN (*Heterodera glycines*) decreases soybean yield more than any other soybean disease (Koenning and Wrather 2010). In the area of field crop nematicide development, the SCN and the root-knot nematode (*Meloidogyne incognita*), which affects many hosts in the southern region, are the main targets within North America. As pesticides continue to be developed, all compounds are screened for additional activity to other targets. For example, a compound that is classified as a fungicide, fluopyram—an SDHI—has been investigated for nematicidal potential against root-knot and reniform nematode (*Rotylenchulus reniformis*). Faske and Hurd (2015) found that fluopyram was nematistatic and low concentrations effectively decreased nematode injury on tomato roots. In greenhouse trials, seed treatments containing fluopyram significantly decreased SCN numbers compared to those without the fungicide (Broderick, Arneson, and Giesler 2015).

As continuous cropping of specific commodities continues, it becomes more difficult to manage nematodes effectively and a range of methods is needed to mitigate their impact. In soybean production, the current field populations of SCN are continuing to overcome the common SCN resistance management practices, so additional options such as nematicides are needed by soybean farmers. Even if tools such as RNAi (ribonucleic acid interference) materialize, there will be a need to protect the investment in that technology by having additional methods of decreasing nematode survival.

COSTS OF SEED TREATMENTS

In many instances, fungicide seed treatments are viewed as insurance to protect the seed from pathogens and ensure a good crop stand. It is not a treatment that consistently returns on the investment by the farmer, but it may be cost effective over several years for fields with a history of stand problems caused by pathogens. Resistance risks for seed treatments are limited because the overall fungicide exposure level for plant pathogens is relatively low; they are not as mobile as arthropods and attracted to the plants. Mobile pathogens, such as water molds (*Pythium* and *Phytophthora* spp.) and nematodes, would be exceptions and pose the greatest risk for resistance to seed treatments. All of the mobile organisms that have sexual recombination and an associated complex genetic structure, however, are less likely to develop resistance than asexual-reproducing organisms (Brent and Holloman 2007a). Many arthropods are mobile and immigrate to the treatment zone of plants with chemistry systematically incorporated into the plant tissues, and therefore they are exposed to greater selection pressure.

The cost of insecticidal seed treatment can vary widely. In soybean the cost can vary from approximately $17 to $35 per ha ($7 to $14 per acre) (Myers et al. 2014) depending on the product used. Hurley and Mitchell (2017) report a cost of just over $17.50 per ha ($7 per acre) and an average return on investment of $42.50 per ha ($17 per acre) (a positive cost/benefit ratio) for U.S. farmers. For cotton, insecticidal seed treatment costs can range from $7 to more than $20 per acre ($17.50 to $50 per ha) (Williams 2010, 2011, 2012, 2013, 2014, 2015). For melons, insecticide seed treatments cost approximately $3 per 1,000 seeds, and at a seeding rate of 20,000 seeds per ha (8,000 seeds per acre) that treatment costs approximately $60 per ha ($24 per acre).

THE ROLE OF EMERGING CROP PROTECTION TECHNOLOGY SOLUTIONS IN INTEGRATED PEST MANAGEMENT

New Technologies in Surveillance and Pesticide Application

Pest surveillance is an integral component and prerequisite for IPM practices, whether invasive, HR, or non-HR weed populations; a fungicide-resistant fungal disease; or an invasive or resistant pathogen or insect species. The potential use of small unmanned aircraft systems (or drones) has been considered for weed research (Rasmussen et al. 2013) and as a general pest management technology (Stehr 2015). Drones might be used to survey for weeds (Calha, Sousa, and González-Andújar 2014; Garcia-Ruiz, Wulfsohn, and Rasmussen 2015; Tamouridou et al. 2016), insects (MacRae et al. 2016), and diseased plants (Lucas 2011). Drones offer good potential for site-specific pesticide application in commercial-scale fields or monitoring pest populations over much larger areas. Advantages of using drone-borne sensors vs. ground-based sensors on sprayers are that drones can cover large areas in a short period of time and pests can be mapped before control is performed to allow planning of pesticide choice and adjustment of spray application parameters. The distinction and quantification, however, of specific disease, insect, and weed infestations from drone imagery are still a challenge. Moreover, although image acquisition is relatively easy, automated analysis and interpretation of the data are more difficult.

Another component of monitoring is real-time release of observations. The Integrated Pest Management–Pest Information Platform for Extension and Education (ipmPIPE) is a web-based database of current observations for diseases that do not overwinter locally and pose a significant threat when they move into a geographic region. Observations at this site include soybean rust, southern corn rust, and cucurbit downy mildew (https://

www.ipmpipe.org/). Having a real-time release of observations combined with the tools being developed with pest management data analysis and remote sensing could develop into a very powerful tool for IPM strategies.

The automation of pest management data analysis will continue to improve as more systems are developed for handling larger data sets. Whether by growers, land managers, or crop advisors on the ground, or by drones or other remote-sensing devices, more systematic, routine monitoring and reporting of HR or invasive weeds on a state/provincial and national level would facilitate awareness and implementation of timely management. Such alert systems are much more common for insect pests, such as diamondback moth, and plant pathogens in soybeans, strawberries, and a few additional crops. The major deterrent to this goal is the lengthy time period required for verification in the field of herbicide resistance in weeds or detection of range expansion of alien invasive species.

One application of map data that can be derived from remote sensing is site-specific management. The premise underpinning site-specific weed management is that the distribution of weeds is aggregated or patchy (Gerhards 2010; Marshall 1988; Wiles et al. 1992) and patches are generally stable (Rew and Cussans 1995; Wilson and Brain 1991). Factors that affect the stability of patches include natural seed dispersal (e.g., wind, dehiscence), tillage, combine harvesting, herbicides, pollen-mediated gene flow, seed persistence, and seed predation. Weed population abundance may be mapped before herbicide application by scouting or estimated in real time using sensors mounted on sprayers. These approaches currently are used mainly for fallow land or row crops and primarily provide an opportunity to decrease the pesticide load in the environment (Lopez-Granados 2011).

Economically important weeds and those that tend to have a patchy distribution are suitable candidates for site-specific weed management. For example, there were economic benefits of herbicide application based on weed presence or absence in spatial maps for wild oat (*Avena fatua* L.) control in wheat fields in the northern Great Plains (Luschei et al. 2001). In spring cereals, site-specific herbicide applications on areas previously mapped as containing wild oats generated higher net returns than blanket herbicide applications, even with the associated mapping costs (Van Wychen et al. 2002). Weed management based on slope position resulted in similar overall weed control with decreased herbicide use compared with blanket applications (Beckie and Shirriff 2012). Additionally, site-specific management can be useful in monitoring and managing HR or invasive weed patches at early stages of development. Preventing seed production and shed in HR weed patches can markedly slow the rate of patch expansion, thus extending herbicide effectiveness in a field (Beckie, Hall, and Schuba 2005).

Advanced pesticide application equipment is required to apply multiple pesticides independently and accomplish the variable-rate spraying required for site-specific pest management. “Smart” sprayers contain both a detection system and a chemical spraying system. The detection system is used to collect information on target areas and make spraying decisions. Various sensing technologies, such as machine vision, spectral analysis, and remote sensing, are used for detection. Three major technical challenges, due to uncontrolled environmental conditions, are confronting sensor application in pest management: (1) variable lighting conditions; (2) leaf coverage, e.g., weeds that grow near crop plants are difficult to measure and classify; and (3) growth status of the target plant(s). In the future, sensing techniques will involve more than one or two detection sensors (Hong, Minzan, and Zhang 2012).

Cultivators such as the rotary hoe have been developed to control weeds within crop rows. This equipment is especially important to organic and vegetable crop growers. Organic and specialty crop producers have few pesticide options for managing weeds; therefore, these production systems rely on crop rotation, cultural practices, and mechanical practices for controlling weeds (Fennimore and Doohan 2008). Rotary hoes and similar in-row equipment must be used at the proper time of crop development or they can cause crop stand loss. In addition, cultivation must be timed to avoid wet fields or other conditions that can decrease its effectiveness. Small seedling annual weeds are most susceptible to cultivation. Hand labor often is required for complete weed control. Thermal technologies, including soil solarization and flaming to control weeds prior to crop establishment and for between-row cultivation, have also been developed (Bond and Grundy 2000). Success of flaming methods depends on weed size, morphology, life cycle, soil moisture, and crop tolerance.

The future adoption of site-specific herbicide application or inter-row tillage will depend on continuing advances in real-time technology that can reliably discriminate the crop from weeds. A number of studies have described the rapid progress in achieving this goal (Christensen et al. 2009; Longchamps et al. 2012; Rydberg et al. 2007; Weis and Sokefeld 2010; Young 2012). During the past decade, rapid advancements in automation and real-time recognition have occurred for robotic weed control in vegetable cropping systems (Slaughter, Giles, and Downey 2008; Zijlstra et al. 2011). A number of autonomous vehicles for inter-row weeding on a small scale have already been developed (e.g., Agricultural Robotics Portal n.d.) in addition to vision-based detection and microcontrol in cropping systems (Blasco et al. 2002; Nieuwenhuizen, Hofstee, and van Henten 2010). Additionally, there is good potential for precision planting accompanied by accurate intra-row weeding (Lati et al., in press; Perez-Ruiz et al. 2014). Eventually, growers will have the technology to vary crop cultivar and planting density according to field soil type or landscape position. For example, some cultivars may yield best on sandy soils versus clay soils, or in low areas of the field versus knolls. This approach may be tried by early adopters but, as a future technology, how cost effective this technology will be is not yet known.

RNA Interference (RNAi)

Ribonucleic acid interference refers to the process of an antisense strand of RNA silencing the complementary endogenous messenger RNA (mRNA), and hence the target gene. Ribonucleic acid used for interference can be short sections of single-stranded (ssRNA) or double-stranded RNA (dsRNA). The ssRNA or dsRNA is processed by the protein dicer into small RNAi that binds to other proteins, including argonaute, to form the RNA-induced silencing complex. This complex binds to a homologous region of mRNA produced by the target gene and destroys it, thereby suppressing gene expression.

First described in the nematode *Caenorhabditis elegans* (Fire et al. 1998), RNAi was discovered accidentally in plants while trying to breed darker petunias by introducing additional copies of the pigment gene (Kupferschmidt 2013). The RNAi mechanism may have evolved to fight parasitic nucleotide (such as viruses) infections in plants and animals (Ding 2010; Katoch and Thakur 2013; Vaucheret and Fagard 2001; Zamore 2004).

Ribonucleic acid interference technology has served as an essential tool for determining gene function in a variety of biological species. Until the development of RNAi, gene function studies were restricted to model systems in which sufficient genetic information was available. Ribonucleic acid interference, sequencing advances, and bioinformatics have changed this, allowing detailed knock-out experiments to determine and validate gene function in nonmodel systems. More recently, this technology has been focused on pest control.

The field of RNAi for pest control may still be in its early stages of development (Figure 1). The number of papers and patents filed or published before approximately 2006 related to RNAi for pest management was very low, but it has been increasing at a steady state. When this technology reaches its full potential, the number of patents, manuscripts, and products should increase exponentially. The only two commercial products presumably based on RNAi released prior to 2006 were transgenic papaya resistant to papaya ring spot virus and transgenic squash resistant to zucchini yellow mosaic, watermelon mosaic, and cucumber mosaic viruses (Fuchs and Gonsalves 2007).

The deregulation and commercial release of transgenic virus resistance in plants employing post-transcriptional gene silencing occurred in 1998 with the release of two varieties of papaya, Sunup and Rainbow (Callis 2013; Gonsalves 1998). Post-transcriptional gene silencing and RNAi appear to be synonymous, because the processes involve the same suite of proteins and pathways (Huvenne and Smagghe 2010; Leibman et al. 2011; Nomura et al. 2004). The two transgenic papaya varieties were developed through backcrossing to recurrent parents from a transformed papaya line generated using gene gun technology; the virus coat protein was the transgene involved (Gonsalves 1998). Although the development of these resistant varieties is credited with saving the papaya industry in Hawaii (Callis 2013), the deregulation and commercial release created significant public outcry against transgenics in that state. The anti-GMO (genetically modified organism) sentiment has led to vandalism of transgenic papaya plantations on the island of Hawaii (Anonymous 2011) and state legislature efforts to ban the production of transgenic plants (Bunge 2014; Harmon 2014a,b).

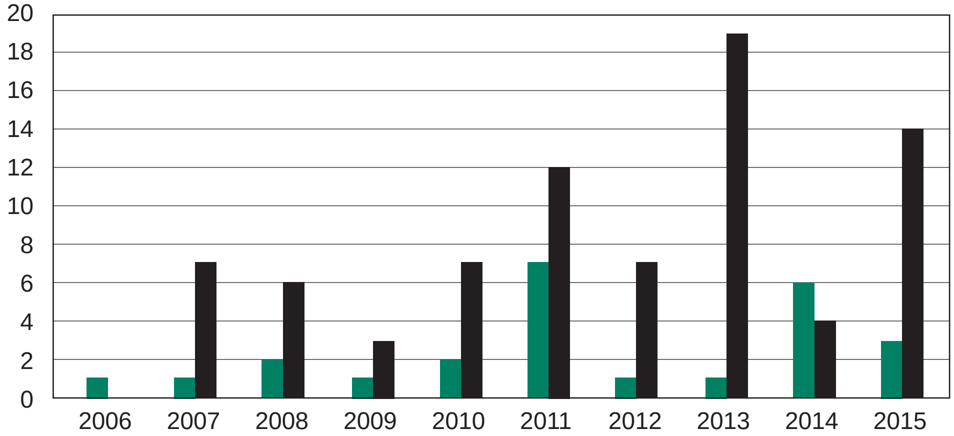

Figure 1. Annual frequency of primary scientific articles and patents about the use of RNAi in pest management for the past decade (2006–2015).
Green bars indicate the number of patents filed for RNAi crop protection products, and black bars indicate the number of scientific publications related to RNAi and pest management.

In the patent search, the targets for control included fungal plant pathogens, Lepidoptera, pathogens on bees, termites, plant parasitic nematodes (*Pratylenchus* and *Meloidogyne*), Coleoptera, citrus pathogens, ants, and Hemiptera. Agricola was used to search the literature using the terms RNA interference and insects, pathogens and weeds, and pest management. Studies focused on determining gene function were not included.

No other commercial products based on RNAi against plant diseases are available, but development of either transgenic or sprayable RNAi products against viral and fungal pathogens has been pursued in economically important solanaceous crops, rice, and cassava (Katoch and Thakur 2013; Koch et al. 2013; Zhang et al. 2011). Efforts to develop a transgenic RNAi product in soybean against SCN are also under way (Guo et al. 2015). In addition, sprayable RNAi technology is being investigated for controlling GR weeds, with Monsanto Corporation developing a sprayable RNAi product (BioDirect™) that will target the 5-enolpyruvyl-shikimate-3-phosphate synthase protein, the same target as glyphosate (Hollomon 2012). Adjuvants will expand the utility of sprayable RNAi by protecting the RNA strands (Mitter et al. 2016).

Regarding insects, RNAi technology has advanced furthest against beetles, moths, and some true bugs (Scott et al. 2013). Within these larger taxonomic groups, substantial variability exists in the effectiveness of this strategy. There are significant differences among insect taxa in their ability to take up RNAi molecules, and this limitation may restrict their broader utility until technological advances overcome this barrier. In addition, Lepidoptera are not particularly susceptible to RNAi and this has resistance development implications. Sprayable

RNAi technology has been developed against Colorado potato beetle (Miguel and Scott 2016; Zhang et al. 2015). The Monsanto Corporation appears to be close to releasing a corn rootworm product using the transgenic RNAi strategy (MON 87411). The RNAi targets the corn rootworm gene DvSnf7. The event (MON 87411) has been deregulated by the U.S. Department of Agriculture (USDA) (Plume and Huffstutter 2015) and cleared the EPA "finding of no significant impact" assessment (USDA–APHIS 2015). The proposed commercial release date for the MON 87411 event is sometime in 2017.

Use of the RNAi technology may fit well into IPM systems because it can be highly selective and delivered in many different ways. The selectivity of the product will depend, in part, on gene selection (Scott et al. 2013), and therefore it is impossible to say categorically that all RNAi projects will be selective. If a target gene is chosen that is highly conserved across multiple taxa, the resulting product may not be selective. Numerous potential delivery systems exist for this technology, including sprays, baits, and engineered plants, expressing the products that could further enhance selectivity (Scott et al. 2013).

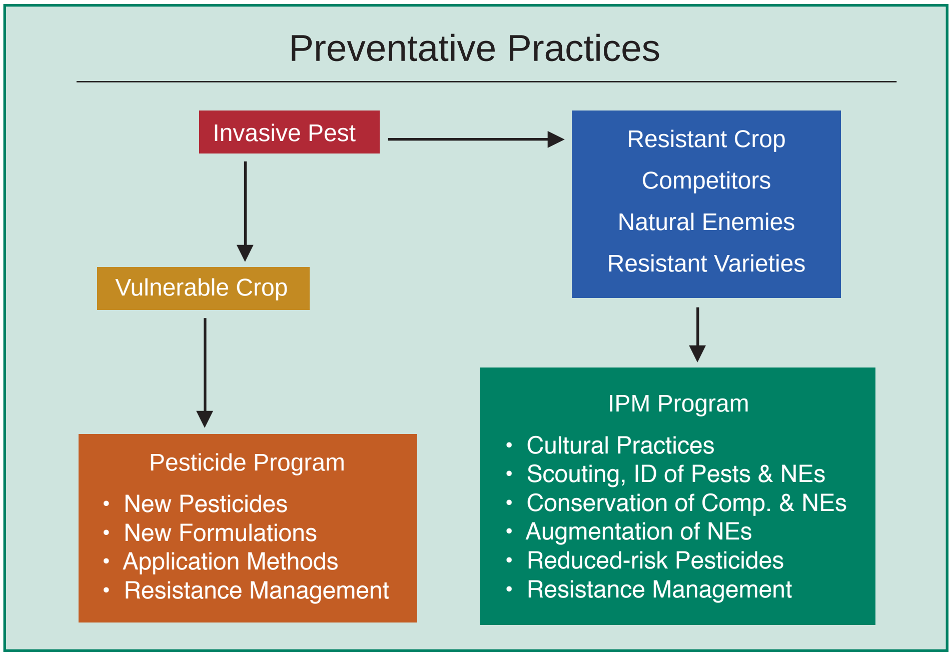

Figure 2. Pest management programs for vulnerable and resistant crops.

When an invasive pest attacks a vulnerable crop, one that is protected only by a pesticide program, the only options are to develop new pesticides and formulations, optimize application methods, and manage pesticide resistance. A more sustainable approach is to create a resistant crop by planting resistant varieties, conserving natural enemies (NEs) and species that are competitors (comp.) with the pest, employing cultural practices that minimize pest pressure (possibly releasing additional NEs), applying pesticides that have few nontarget effects, and minimizing the development of pesticide-resistant pests (Demirozer et al. 2012; Reitz et al. 2003).

Prophylactic- vs. Threshold-based Pesticide Uses

Pest and disease prevention is one of the basic principles of IPM (National IPM Program 2013), but this does not include constantly maintaining a pesticide barrier around a crop. A strategy based on prophylactic pesticide use alone is expensive and ultimately results in increased environmental impacts and resistance development, in addition to potential pest resurgence and secondary pest outbreaks (Demirozer et al. 2012; Radcliffe, Hutchinson, and Cancelado 2009). It creates a vulnerable crop that can be protected only temporarily by applying pesticides more effectively, more often, or in greater amounts. Ultimately, new pesticides will be needed with different MOAs as replacements or for rotation, and pesticides are becoming more expensive (see Figure 2).

A sustainable approach to managing pests is to establish a pest-resistant crop by planting less susceptible cultivars and using cultural practices that limit pest survival and reproduction, such as crop rotation and sanitation, while preserving competitors and natural enemies. Reduced-risk pesticides are used sparingly based on scouting and general thresholds for pest populations. Resistance management is practiced to preserve pesticides. Establishing and optimizing an IPM system is a long-term investment that requires in-depth knowledge of the crop, the biology of pests and diseases, and associated pest management tactics. It is especially important to not grow other crops or tolerate weeds that are alternative hosts for the pests and to establish area-wide action by local growers. It is necessary to monitor crop conditions, such as weather, past pesticide use, pests and diseases, beneficial organisms, and cultural practices (e.g., irrigation and fertilization), to determine if intervention is needed and will result in an economic benefit (MacKenzie and Peres 2012; Pavan, Fraisse, and Peres 2011; Radcliffe, Hutchinson, and Cancelado 2009). Regional surveillance systems have been developed to provide soybean, corn, onion, and pecan growers, among others, with near real-time information on the distribution and severity of selected insect pests and plant diseases (Hershman, Sikora, and Giesler 2011; Montana State University n.d.; VanKirk et al. 2012). Web-based decision support tools based on climatic data are now widely available (Oregon State University n.d.).

Based on these kinds of surveillance systems, scouting, and experience, a grower can decide what economic injury level (Stern et al. 1959) will trigger interventions that are least disruptive to the established IPM system. Crop advisors, possibly doctors of plant medicine (University of Florida 2015), assist the growers in deciding when an action threshold has been reached. The grower must be vigilant and ready to act quickly before the pests or diseases reach outbreak or epidemic levels and are extremely expensive or impossible to control.

Before initiating a pest management plan, it is vital to assess pest status in relation to the crop and nearby habitat. This should be done by monitoring; any subsequent suppression should rely on IPM strategies to ensure that intervention is needed and will result in an economic benefit (Naranjo et al. 1998; Radcliffe, Hutchinson, and Cancelado 2009). The use of economic thresholds for insect pests has been deployed along with the concepts of economic injury levels and integrated control since 1959 (Stern et al. 1959). Spraying insecticides on a schedule when control measures are not necessary results in increased environmental impacts and resistance development, in addition to potential pest resurgence and secondary pest outbreaks. Although the use of these IPM concepts has proven successful for many insect pests, this approach does not necessarily translate to the management of plant pathogens and weeds because of the reproductive capacity and dispersal of these types of pests.

Plant Pathogen Thresholds

In plant disease management, farmers and crop managers are in need of thresholds; however, the complexity of disease development has made this an almost impossible task for researchers. With newer technologies and forecasting models becoming better (such as those found on the Oregon State University [n.d.] website), this should be a priority for development in the coming years. In many cases, fungicide applications are made and may not be cost effective (Wise and Mueller 2011). In a summary of 33 trial reports for corn fungicide applications and yield results, only 48% of 472 treatments resulted in an economic increase in corn yield based on prices in 2011. In this summary, there was a strong correlation between disease severity and its impact on yields, demonstrating the need for applications to be driven by disease pressure.

Plant genetics, the cropping system, and the environment all contribute to overall disease development, which makes each field a unique observation and treatable unit, just like other pest management systems. The greatest differences are the complex interactions and the ability of plants to yield in the presence of disease development, in some cases. In addition to scouting for specific diseases being present, the most practical integrated management decision aid is a disease forecasting model. Currently, the risk of scab, a disease caused by *Fusarium graminearum* infecting the wheat crop at flowering, is managed with the aid of disease forecasting that uses current weather data and geography (De Wolf, Madden, and Lipps 2003). The same is true for apple and pear scab in the west (Oregon State University n.d.). These models have been continually refined since their initial development, and there is a significant need to have similar tools available for effective IPM practices to be developed for other diseases such as southern rust of corn, which has a monitoring component on the ipmPIPE, and *Sclerotinia* diseases, for which there is a national initiative for study across the United States.

Weed Thresholds

The use of thresholds to assist growers with weed management decisions has been debated since the concept was introduced for arthropod management in the 1950s (Norris 1999). Scientists have documented the effect of weeds and weed complexes on crop yield, often finding that variability in response is due to a number of primary interacting factors, including crop and cultivar, weed densities and species interactions, weed time of emergence and management practices, and environmental conditions (Aldrich 1987; Norris 1999; Swanton et al. 1999).

Coble and Mortensen (1992) reviewed use of the economic threshold concept based on an assessment of the weed population using a competitive index. This approach was limited to crops that had registered selective post-emergence herbicides. Norris (1999) and Buhler, Liebman, and Obrycki (2000) pointed out that biological and ecological differences between insects and weeds must be considered when assessing whether or not the threshold concept as practiced for arthropod management is appropriate for weed management. Some of the considerations include the fact that weeds and insects use different resources for food; weeds persist over time in the field as seed (with persistence aggravated by characteristics such as dormancy and seed coat structure), whereas most insect populations do not carry over in a field from year to year; fecundity of weeds is 10 to 1,000 times greater than insects; and generation time and population dynamics differ between weeds and insects. Because uncontrolled weeds can produce tens of thousands to hundreds of thousands of seeds per individual and can remain dormant in the seed bank over time, the weed problem in subsequent years can become unmanageable; therefore, any development of thresholds for weed management must necessarily take a multiyear approach. Additionally, the concept of weed damage thresholds that trigger herbicide application is losing credibility in weed science because of increased focus on weed seed control to mitigate HR weed population abundance.

Weed scientists who work with specialty and organic crop growers have long stressed the need to manage the soil seed bank by decreasing seed inputs and managing the soil and crop environment to enhance seed predation and decay and to lessen the probability of weed establishment (Davis 2006; Gallandt 2006; Norris 1999; Schutte and Cunningham 2015). Additional considerations for determining which weed species must be managed at zero tolerance include the effect of the weed species on the soil-pest complex (Sanogo et al. 2013; Schroeder, Thomas, and Murray 2005). Realistically, this approach is only applicable to row crops, such as cotton, where mechanical or manual weeding within the crop is possible. Research on weed biology, seed bank dynamics, weed population dynamics, and crop production economics is needed to determine the feasibility of integrated weed management (IWM) strategies that include decision tools, such as economic optimum thresholds established using bioeconomic models (Bagavathiannan and Norsworthy 2012).

Genetic Methods of Pest Management

Traditional breeding for improved cultivars with resistance or tolerance to plant pathogens and insect pests has been the mainstay of decreasing their impact. With the continued evolution of pests that become resistant to management methods, there has been a continued need for breeding efforts to “stay ahead” of the pests. This is especially true when single gene or monogenic resistance mechanisms are used. Marker technology used to genotype plants and animals has advanced quickly, giving rise to widespread availability of marker-assisted selection used in plant breeding. The details of the marker-assisted selection and tools used are beyond the scope of this paper; however, these advances have been crucial for developing native resistance traits (those traits normally found within the plant genome as opposed to those introduced from a different organism). The marker and sequencing technology advances have made insertion site characterization much easier, faster, and more certain, and this allows the introduction of resistance traits from wild (undomesticated) progenitors into elite germplasm without bringing along many of the undesirable traits that can affect yield from the ancestral genomes. This cuts the time needed for development of resistant cultivars in breeding programs in half (at least). Insertion site characterization will also facilitate the registration of new transgenic plant traits engineered to resist insect damage.

Transgenic insects are being created to be self-limiting. *Aedes aegypti* (L.) mosquitoes are genetically modified to produce males only in the laboratory for release to mate with wild-type females that will produce no viable progeny. This sterile insect technique approach has been tested for use on a wide variety of insect pests, such as additional mosquito species (Alphey et al. 2010), the pink bollworm (*Pectinophora gossypiella* [Saunders]), the diamondback moth (*Plutella xylostella* [L.]), the spotted winged drosophila (*Drosophila suzukii* [Matsumura]), tephritid fruit flies (*Ceratitis capitata* [Wiedemann]), the new world screwworm fly (*Cochliomyia hominivorax* [Coquerel]), and many others (Benedict 2014).

Plant-incorporated Protectants (PIPs)

The discovery of proteinaceous insect control products from the bacterium *Bacillus thuringiensis* (*Bt*) and advances in bioengineering and bioinformatics have drastically changed the thinking about insect control. Engineering plants to produce plant protectants themselves, albeit constitutively, has become much easier over the past decade because of technology advances. Crops in several plant families have been transformed to express proteins from the *Bt* bacterium, and some of these products have been instrumental in controlling significant insect pests, for example, Cry1AB and Cry1F in corn to control European corn borer in the midwestern United States (Pereira et al. 2008). There are three *Bt* cottons: Bollgard II, WideStrike, and WideStrike III. Both Bollgard II and WideStrike contain the Cry1Ac toxin. Bollgard II also contains the Cry2Ab toxin and WideStrike contains the Cry1F toxin. WideStrike III contains not only Cry1Ac and Cry1F, but also Vip3*A*. Although *Bt* cottons generally provide excellent control of most lepidopteran larvae, they are not immune to damage caused by other arthropods, especially plant and stink bugs. The pink bollworm has been effectively suppressed in Arizona using *Bt* cotton in an area-wide program (Naranjo 2010).

Crops with Resistance to Multiple Herbicides: Stacked Traits

Industry response to increasing incidence and complexity of HR weeds and to lack of new MOA herbicides has been to develop multiple-trait (stacked) HR crops. Combinations of HR traits include glyphosate, glufosinate, acetolactate synthase inhibitors, hydroxyphenylpyruvate dioxygenase inhibitors, and synthetic auxins (2,4-D, dicamba) (Duke 2012; Green 2014). For example, crops with stacked traits include glyphosate- plus glufosinate-, glyphosate- plus 2,4-D, or glyphosate- plus dicamba-resistant soybean, corn, and cotton. This strategy is generally viewed as giving enhanced flexibility to growers to cost effectively manage weed resistance through herbicide mixtures and sequences within a growing season, or herbicide rotations across growing seasons, provided that sufficient herbicide MOA diversity is maintained in rotations involving crops with stacked traits (Carpenter and Gianessi 2010; Green et al. 2008). Numerous weed populations, however, are already resistant to one or more of these herbicide MOAs (Heap 2016), suggesting that they must be integrated with other weed control methods to remain effective.

HOW TO PRESERVE CROP PROTECTION CHEMISTRIES AND TRAITS—EFFICACY, DURABILITY, AND USEFULNESS INTO THE FUTURE

Resistance Management

Pest resistance to any pesticide or genetic trait is one of the greatest concerns when a plant protection product is developed, released, and deployed. Although there are many examples of proposed methods for decreasing the potential for resistance development, actual field scale experiments to validate best management practice to decrease pest resistance are limited. Broad adoption of novel pest management tools combined with lack of rotation and off-label usage of pesticides have contributed to resistance issues in weed, plant pathogen, and insect populations (Bethke 2002).

The Fungicide Resistance Action Committee (FRAC) was formed in 1981 and is primarily a group composed of agricultural company fungicide development specialists. Their goal is to provide fungicide resistance management guidelines to prolong the effectiveness of “at risk” fungicides. This group develops resources to facilitate durable product development and limit crop losses should resistance occur.

In 1991, a review—“Fungicide Resistance: Practical Experience with Antisense Strategies and the Role of Integrated Use”—discussed crop management concepts to manage pathogen resistance, including cultivar susceptibility, nitrogen (N) fertility, sanitation, and recommending fungicide use only when justified and under low disease pressure (Staub 1991). Staub recommends judicious use of fungicides in mixtures with residual activity and that product selection criteria should consider persistence and systemic characteristics.

There is an extensive list of plant pathogens around the world that have developed resistance to fungicides, and the list continues to grow. The most recent combined report on the FRAC website is for 2013 (FRAC 2014), and the most recent event affecting agriculture in North America is resistance to frogeye leaf spot of soybean (*Cercospora sojina*) reported in 2010 (Zhang, Newman, and Bradley 2012). Most companies have adopted more combination MOA products over the last 10 years. In 2010, FRAC published recommendations for fungicide mixtures designed to delay resistance evolution and suggested all new products being developed by the larger (nongeneric formulating) companies include two or more MOAs (FRAC 2010). Based on current agricultural trends to maximize productivity and increase acreage being treated with fungicides, there is a need for new MOAs in disease management and for industry to continue to evaluate potential chemical targets. By using the managing strategies that are clearly outlined in the FRAC resources (Brent and Hollomon 2007b), the shelf life of chemical products will be maximized and diligence will minimize the risk of developing resistance.

Insect resistance management (IRM) has been one of the most significant concerns related to the use of constitutive PIPs, especially engineered ones. Genetics, ecology, and modeling have played important roles in developing the IRM plans for crops expressing *Bt* proteins (Tabashnik, Brevault, and Carriere 2013). The IRM plan for preventing resistance development against *Bt* proteins in plants relies on the “high-dose refuge strategy” (Tabashnik, Brevault, and Carriere 2013), which in turn relies on large numbers of susceptible individuals being available to mate with the few resistant individuals produced from the transgenic *Bt* crop. When the susceptible and resistant individuals mate, the resulting progeny should be susceptible to the *Bt* proteins expressed within the plant. The strategy relies on the recessive inheritance of resistance, low-resistance allele frequency, and an abundant refuge producing large numbers of susceptible individuals.

Fitness costs associated with resistance further prevent its development. Although *Bt* crops have been available for nearly two decades within the United States and Canada, there have been only three cases of resistance that are of concern, because of the speed of development (< 10 years) and the level of resistance (decreased efficacy reported): Cry2Ab used to control cotton bollworm, Cry3Bb1 used to control corn rootworm, and Cry1F used to control fall armyworm (Tabashnik, Brevault, and Carriere 2013).

Recent modeling efforts have demonstrated that multiple PIPs acting in concert can slow the rate of resistance development in those cases in which the high dose of one individual PIP may not be achieved. There are examples of transgenic plant products expressing *Bt* proteins in which the level of expression does not meet the requirements of high dose (a dose 25 times the concentration necessary to kill susceptible larvae) (USEPA 2001), and in those cases resistance management is a concern. Seed treatment products that can be translocated to aboveground parts of the plant where the target insect is feeding, however, may decrease the likelihood of resistance development and increase the product life of the *Bt* transgenic plant (Aupperle et al. 2015).

Evolution of weed resistance to herbicides has been an issue since the introduction of selective herbicides more than 50 years ago. The problem has gained urgency and public attention because of the agronomic or environmental impact of 20 years of cultivating HR crops in North America, dominated by glyphosate resistance. In contrast to IRM, refuge of susceptible individuals to delay herbicide resistance is not feasible because of the dominant or semi-dominant inheritance of resistance in most cases. Moreover, fitness costs associated with GR weeds have not been consistently detected. The increase in HR (especially GR) weed populations has prompted renewed focus on managing the seed bank to mitigate HR weed population abundance, often through a zero tolerance for weed seed production (Barber et al 2015; Norris 1999).

A relatively new tool for decreasing weed seed return to the soil seed bank in field crops is the Harrington Seed Destructor™ (Walsh and Powles 2014; Walsh, Harrington, and Powles 2012). Targeting weed seeds at harvest—primarily via chaff carts or narrow windrow burning—is a major focus of growers in Western Australia, and the majority of these growers are optimistic about the future of grain cropping despite high incidence of HR weeds. The Harrington Seed Destructor, narrow windrow burning, and chaff cart treatments each decreased annual ryegrass (*Lolium rigidum* Gaud.) emergence by 55% compared with nontreated controls (Walsh and Powles 2014). Substituting windrow burning with alternative methods of weed seed destruction or capture would be more environmentally friendly. The technology is promising for those weed species with minimal seed shatter prior to crop harvest. Research is ongoing to determine the species of concern that shows minimal seed shatter prior to harvest (Burton et al. 2016). The technology, however, must be integrated with other weed management tools to avoid selecting for early-maturing phenotypes (Ashworth et al. 2016). Therefore, basic weed biology information needs to be known for key weed species in early- and late-maturing crops in an agroecoregion.

Cover crops, including green manure crops such as sweetclover (*Melilotus officianalis* L. Lam) or red clover (*Trifolium pretense* L.), not only inhibit weed emergence and growth, but also fix N. Cover crops are widely used by organic growers, but not by conventional growers (Blackshaw et al. 2008). For managing GR Palmer amaranth or other species in southern U.S. cotton and soybean, however, cover crops are becoming an increasingly important component of HR weed management (DeVore, Norsworthy, and Brye 2012). Replacement of chemically induced fallow fields in the Great Plains with cover crops is needed because of high selection pressure on bare ground for GR weeds, such as kochia (*Kochia scoparia* [L.] Schrad.) (Beckie et al. 2013).

Persuading growers to include cover crops will require continuing research on their cost effectiveness and integration into current production and pest management systems, particularly for managing GR and multiple-HR weeds. An additional factor that must be considered and researched is to ensure that cover crops are compatible with other pest management and soil management objectives. Plant breeding research is being conducted to produce cover crops that self-destruct after they have suppressed weeds but before they begin competing with the crop, based on high temperature, photoperiod, or moisture stress cues (Shaner and Beckie 2014; Stanislaus and Cheng 2002; Tranel and Horvath 2009). An additional consideration in development or selection of cover crops for a specific cropping system or environment, in addition to weed suppression and termination, is whether or not they host or otherwise impact populations of other pest species.

Regardless of cropping system, there is a great need for cost-effective, sustainable weed control practices to help growers diversify their weed management programs, maintain agricultural productivity, and manage populations of HR weeds. Growers need all options available to manage weeds. Mechanical or physical weed control has traditionally been one of the pillars of IWM. Timely, strategic, or precision tillage, as it has been labeled, to manage weeds does not necessarily jeopardize soil quality, built up after years of no-tillage—provided that crop residue cover on the soil surface is maintained (Baan, Grevers, and Schoenau 2009). For example, management practices that combine strategic tillage with cover crops and herbicides are being evaluated and recommended to growers who are managing GR Palmer amaranth in the southern United States (DeVore, Norsworthy, and Brye 2013; Price et al. 2016; Wiggins et al. 2015). Hand weeding is a labor-intensive weed management practice. The cost is increasing and availability of a labor force for hand weeding is increasingly scarce because of competition from nonagricultural industries and immigration issues (Fennimore and Doohan 2008; Taylor, Charlton, and Yunez-Naude 2012).

Yield and Quality Enhancement

Increased yields and improved crop quality from pesticides and genetically modified crops are well documented since their introductions in the crop protection marketplace (Brookes and Barfoot 2013; CAST 2014). From 1996 to 2015, *Bt* cotton and maize contributed to closing the gap between potential and actual yield, although yield results vary because of pest abundance and agricultural practices (National Academies of Sciences, Engineering, and Medicine 2016). Average yield improvements from fungicide use for 50 crops ranging from 16 to 100% were described by Gianessi and Reigner (2006), resulting in an estimated increase of approximately $13 billion in U.S. farm income. The introduction of herbicides, including those used on HR crops, has contributed to yield increases and economic benefits, resulting primarily from decreased weed competition. An additional benefit of the introduction of HR crops has been a 36% reduction in tillage between 1990 and 2009 (CAST 2012). With regard to insecticides, the authors of another CAST paper (CAST 2014) estimate a $19 to $1 return on investment for U.S. growers. Brooks and Barfoot (2015) estimated a $20.5 billion benefit from genetically modified crops in 2013 and since 1996 farm incomes have increased $133.5 billion. It is estimated that between 1996 and 2011, GMO use resulted in an additional 177 million tonnes (195 million tons) of corn and 100 million tonnes (110 million tons) of soybean. As the world population continues to increase, it will be vital to continue to obtain the yield and quality benefits for crop protection technologies; therefore, it is critical to use integrated practices to prevent or delay resistance to these technologies.

SUMMARY

Present and Future Trends

Genomic/Molecular Systems and Their Possible Future Impacts

Rapid sequencing advances now make entire genome sequencing relatively easy and fast. Sequencing devices are available that can fit into your palm and the data can be downloaded to your smartphone. In step with the sequencing advances are the bioinformatics tools necessary for assembling these sequences, along with the advances in computer technology necessary to process, store, and share these large datasets into handheld devices. These genetic tools will permit the rapid characterization of pathogen, insect pest, and weed genotypes in the field, possibly leading to more rapid identification of resistant genotypes. This could be an important method for preventing the development of resistance to new plant protection compounds as well as development of novel resistance mechanisms in crop plants.

A new gene-editing technique, CRISPR-Cas9 (clustered regularly interspaced short palindromic repeats-CRISPR associated), may change the future of crop protection. CRISPR, a highly targeted gene-editing approach, allows deoxyribonucleic acid to be altered rapidly and precisely. CRISPR is based on the enzyme Cas9's ability to lyse genetic material. The approach allows for precise editing of genes and the introduction of new genetic material that metastasizes quickly within a population of organisms (gene drive). CRISPR permits nontransgenic genetic engineering that is an important distinction from genetically modified approaches and, by controlling plants' and animals' trait expression, may prove to be effective in pest management.

Future of Crop Protection

Continuous improvements will be needed in attractants, trap design and efficiency, scouting methods, and rapid verification of pest occurrence. Greater emphasis will be placed on pest exclusion through preclearance at ports of embarkation and port operations of the USDA, Animal and Plant Health Inspection Service, Plant Protection and Quarantine, and Customs and Border Protection at ports of entry. New and improved technologies for pest exclusion and early detection will include advancements in screening (x-ray, volatiles, sound, cameras, passenger and cargo tracking), pest identification (keys, apps), and reconnaissance (drones, visual, consistent sampling).

The Cooperative Agricultural Pest Survey program and associated database is intensifying. Moreover, pest risk analyses involving climate and seasonal pathway mapping aid deployment of surveillance resources. Weather monitoring systems are being developed to more accurately predict pest occurrence and spread as a result of increasing temperature, frontal patterns, and other atmospheric conditions (e.g., lepidopteran pests moving northward from the subtropics each year to infest field crops in the Midwest and southern U.S. states) (Coop et al. 2014; Kriticos et al. 2015). Aphid suction traps have been deployed for decades in Europe and the United States, and there is potential to combine weather stations and traps to rapidly detect the arrival of many other migratory insect pests.

As new insect pests become established and existing ones expand their ranges, real-time geo-referencing capabilities are increasingly used to record their presence. This enables growers to know if action is warranted immediately or how soon it could become necessary. Real-time insect pest and plant disease diagnostic systems will be networked with growers and first responders to prevent the establishment of new invasive insects and diseases. This will be accomplished by increasing the speed, accuracy, and effectiveness of local insect pest and plant disease scouting and identification; increasing high-risk sample submission; enhancing diagnostic capabilities; and minimizing the time required to implement control measures.

Grower Adoption

Decision making in pest management will continue to become more complicated, requiring highly trained growers or, more likely, crop advisors (Kopp and Mayer 2010). Selecting actions that minimize the damage caused by pests and maximize the reliability and profitability of farming requires a means of defining and evaluating the key variables, most likely using commercially available computer software programs. These decision-making tools have become increasingly popular for identifying the causes of insect outbreaks and disease epidemics, monitoring pest population levels, establishing action thresholds, and selecting the best pest management actions. Among the key variables are biological characteristics of the pests, such as their damage potential, ability to vector plant pathogens, reproductive rate, host range, and mobility. Currently, arthropods or diseases that are not suppressed by natural enemies or weather events require interventions to be implemented quickly—e.g., access and use of pesticide application equipment. Although there will be more effective pest management options in the future (Jindal, Dhaliwal, and Koul 2013), they may be too expensive relative to the market value of some crops (Atkinson et al. 2007; BMGF 2007; Buhler, Liebman, and Obrycki 2000). Included in these options will be new insecticide active ingredients, biopesticides, predators and parasitoids, autocidal techniques, attract-and-kill systems, genetically modified pests, and combinations in true IPM systems.

The IPM community is focusing on discerning the human element of pest control to complement efforts on better understanding the biological characteristics of target pests and pest complexes and developing innovative management tactics. There is a growing realization that the status quo is not working, and a multidisciplinary approach is needed to spur adoption of best management practices. Members of two allied disciplines, agricultural economists and sociologists, routinely examine types of agricultural innovation and rates of adoption, capital investment, development, and dissemination of new technologies, knowledge, and information. Factors such as grower demographics, level of knowledge, values and goals, size of the farm operation, commodities produced, local community social structure and networks, market influence and signals, and resource input costs can all influence the decision-making or problem-solving process of a grower.

Moreover, to actually cause the production community to proactively adopt IPM, a better understanding is needed of the most important decision drivers that impact management of all pests across different crop production systems and regions. Increased dialog among all stakeholders—growers, land managers, retailers, applicators, agrichemical companies, university research and extension, crop advisors, and state and federal departments or agencies—should result in a better understanding of how best to approach IPM planning and implementation.

Growers will not adopt recommendations perceived as being too expensive (or as expensive as current practice), time consuming, or complicated. Successful IPM systems in the future, however, will inevitably require more knowledge, planning, time, cost, and possibly risk by growers than in the past (Swanton et al. 2008). The history of weed control in the industrialized countries over the past half century has shown that cost, simplicity, and convenience are the top three criteria for pest management decisions by growers. Because of the risky nature of farming, it is difficult for many growers to act long term when the economic viability of their farm enterprise is at stake. Moreover, growers who rent or lease land, comprising a substantial proportion of all growers (e.g., 40% in Canada [Statistics Canada 2012]), may have less incentive for land stewardship, including adoption of IPM practices, than operators who own the land. Growers, especially when they are renters rather than owners, greatly discount potential future rewards relative to present ones. Moreover, the common gene pool nature of pesticide resistance, particularly those species with efficient long-distance dispersal, may deter individual growers from proactively managing pests.

Success in the war on pests requires a more area-wide, collective adoption of resistance and integrated management practices by neighboring farms across a county or municipality (Llewellyn and Allen 2006). There are examples from the entomology community that have shown how a community-based approach to management of an insect pest across a region has been highly successful (Calkins and Faust 2003; Elliot, Onstad, and Brewer 2008; Hendrichs et al. 2007; Klassen 2005; Knight 2008; Knipling and Stadelbacher 1983; Lindquist and Tan 2000).

If short-term economics drives the decision-making process, then increased IPM adoption by growers will require both industry and government incentives, as well as a strong education and awareness campaign directed at all stakeholders (Barrett, Soteres, and Shaw 2016; Kopp and Mayer 2010). We need to understand, by region, where growers get their pest management information. In a 2005 survey of nearly 1,200 growers in six U.S. states, the top three sources of information on pest issues were farm publications (41%), dealers/retailers (17%), and university extension (14%) (Givens et al. 2011). In a follow-up survey in 2010 involving approximately 1,650 growers in 22 U.S. states, these three sources were 41, 22, and 20%, respectively—similar results to the previous survey (Prince et al. 2012). Moreover, industry must reexamine current stewardship guidelines for growers of stacked-gene crops to deter GMO crop monocultures.

Regulatory Impacts and Adoption

The "Coordinated Framework for Regulation of Biotechnology" published in the *Federal Register* in the mid-1980s describes the federal regulatory policy for ensuring the safety of biotechnology research and products (OSTP 1986). The Coordinated Framework outlines the roles and responsibilities of relevant federal agencies (USDA, EPA, Food and Drug Administration [FDA], and others) and the relevant laws (Plant Pest Act; Federal Insecticide, Fungicide, and Rodenticide Act; Federal Food, Drug, and Cosmetic Act; National Environmental Policy Act) that govern those agencies' activities. The responsibility of the different agencies includes protecting the consumer (FDA) and the environment (USDA and EPA). It was recognized that technological advances could require the Coordinated Framework to evolve (USGAO 2008). Three decades have passed and numerous advances in biotechnology have been made, and in response a memorandum has been issued to update the Coordinated Framework by the EPA, FDA, and USDA to increase public confidence and ensure future innovation and competitive opportunities (White House 2015).

Pest resistance to control tactics is a well-established concern leading to product stewardship initiatives in the public and private sectors. The development of insect-resistant and HR crop plants through the use of molecular biology tools has led to the development of an entire body of literature regarding how these crops should be deployed to minimize the risk of pest resistance. Resistance has developed despite the stewardship efforts. So how should stewardship be changed to avoid resistance in the future? Currently, the debate about stewardship in the public sector revolves around the role of regulatory agencies and the use of incentives or punitive actions (Barrett, Soteres, and Shaw 2016).

The USDA farm and conservation programs could play a greater role in providing incentives for encouraging crop rotation and pest management diversity to minimize the risk of resistance development. Government farm policies, in conjunction with industry incentives via pesticide product pricing, could provide economic incentives to encourage growers to take a more proactive approach to product stewardship. Incentive programs, however, are normally designed to overcome initial economic barriers and therefore are short term. Additionally, incentives may be viewed as subsidies and these could cause problems in bilateral and multilateral free-trade negotiations.

The EPA has announced additional efforts to require detection, reporting, and control of herbicide resistance on the part of herbicide registrants, an approach similar to current requirements for plants transformed to express *Bt* proteins (Housenger 2014; USEPA 2016a,b). Additional regulations on herbicide stewardship could be problematic because enforcement may be difficult or politically untenable in many jurisdictions. Further regulation may also influence the market in unexpected ways. Regulations concerning the percentage of refuge plantings in combination with crops expressing *Bt* proteins have been used by the private sector to gain market advantage. Although integrated refuge compliance is required, the associated refuge reduction from 30 to 5% has become a private sector mechanism to increase sales of high-priced seed.

Integrated Cropping Systems to Address Future Pest Management Issues

The expanding field of agroecology is defining how entire farms can be designed to resist pests, preserve biodiversity, and provide certain ecosystem services (Figure 2). The focus has been on relatively small-scale local production and consumption in developing countries, but many of the principles could be extended to large operations. Unfortunately, many pest management actions do not address the cropping system as a whole, and sometimes the habitat initiatives directly conflict with other pest management recommendations. Weeds in field margins serve as host plants for beneficial insects (Landis et al. 2005), but also for pest arthropods, diseases, and nematodes (Capinera 2005; Davis 2010; Thomas, Schroeder, and Murray 2005; Wisler and Norris 2005). Ineffective management of field margins can exacerbate weed problems, increasing general and HR weed populations if those plants are allowed to mature and set seed (Norsworthy et al. 2012). Detailed pest management plans have recently become a requirement for food distribution companies (e.g., Sysco) that want to maintain high standards of food safety, quality, and traceability. Organic and sustainable certification will continue to increase, and the standards will be harmonized internationally (e.g., GLOBALGAP [good agricultural practices]).

In addition, concern for threats to honey bees, other pollinators, and monarch butterflies in recent years has led to new emphasis on habitat establishment throughout the agricultural landscape. In 2015, the White House published the *National Strategy to Promote the Health of Honey Bees and Other Pollinators* (Pollinator Health Task Force 2015), in which strategies across the federal government to enhance pollinator health, including activities to benefit forage resources and habitat, are described. In 2007, the Canada/Mexico/U.S. Trilateral Committee of Wildlife and Ecosystem Conservation and Management also endorsed the North American Monarch Conservation Plan, which is focused on conservation of the monarch butterfly and its migratory flyway (CEC 2008). Moreover, federal agencies have developed resource materials and incentive programs to encourage establishment and conservation of habitat as part of these initiatives (USDA 2015).

Existing and future plant protection tactics will become increasingly complex, technology driven, expensive, and dependent on preventing pest occurrence or outbreaks. Considerable research is being conducted on cultural practices, such as crop rotation, destruction of crop residues, establishing cover crops, planting strip crops to encourage natural enemies and pollinators, matching crops to the best land and climates, better management of plant nutrition and irrigation, plowing methods to eliminate subterranean pests, timing of planting and harvest dates, use of hedgerows, and field size and isolation. Although not typically considered for pest management, flooding can be very effective for drowning subterranean insects. Many of these preventative practices require area-wide cooperation to decrease insect, disease, and weed pressure by eliminating local sources. Breeding of insect- and disease-resistant plants will remain the primary means of preventing these pests, probably accelerated by using molecular methods. Push-pull systems using repellent plants in combination with others that attract insect pests away from crop plants are being used for a variety of crops, such as corn, sorghum, and vegetables. In order to manage agricultural landscapes to address these complex requirements, scientists from all the pest management disciplines need to improve communication and work together to develop integrated strategies for managing pests while preserving ecosystem services and farm productivity.

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