Field to Market®

Trends in Pest Management in U.S. Agriculture:

Identifying Barriers to Progress and Solutions Through Collective Action

Contributors

Allison Thomson and Eric Coronel, Field to Market; Will Fulwider, Natalie Eisner, Ariel Larson, Matt Lichty, Gabriel Schaffner and Thomas A. Green, IPM Institute of North America.

Acknowledgements

This report benefited greatly from the input of five independent expert reviewers: Steven Bradbury (Iowa State University), David Kerns (Texas A&M University), Christian Krupke (Purdue University), Ed Spevak (St. Louis Zoo) and John Tooker (Pennsylvania State University). While the reviewers provided many constructive comments to improve the report, they were not asked to endorse the conclusions of the report, nor did they see the final draft before release.

We also thank Kelly Young and Chisara Ehiemere of Field to Market for assistance in the development of this report and the members of the Field to Market Pest Management Task Force for their participation in multi-stakeholder discussions that led to the commissioning of this report.

A number of representatives from the following organizations provided feedback on early versions of the data analysis and assisted with data interpretation for individual crop sections: American Peanut Council, American Soybean Association, Cotton Incorporated, National Association of Barley Growers, National Association of Wheat Growers, National Corn Growers Association, National Sorghum Producers, Potato Sustainability Alliance and USA Rice Federation. The authors would also like to thank Field to Market's Board of Directors, member organizations, and staff for their support and guidance.

How to Cite This Report

Citation: Field to Market: The Alliance for Sustainable Agriculture. 2020. Trends in Pest Management in U.S. Agriculture: Identifying Barriers to Progress and Solutions Through Collective Action. 68 pp.

Table of Contents

Key Messages

- Field to Market: The Alliance for Sustainable Agriculture is committed to advancing sustainable agriculture in the United States through a multi-stakeholder, science-based approach to evaluate and continuously improve environmental outcomes at the field and landscape levels.
- There are significant opportunities for the commodity crop value chain to support farmers in adopting responsible pest management practices that can reduce harmful impacts of pesticide use on biodiversity, water quality and human health.
- Many of these same responsible pest management practices are also essential to address the production challenges associated with increasing incidence of pesticide resistance, such as herbicide resistant weeds, that are a source of concern for U.S. farmers.
- Building healthy soils can support healthy, resilient plants; therefore, a broad range of sustainable agriculture practices — including diverse crop rotations, cover crops and reduced tillage — can help to protect against crop damage from pests.
- Farmers must use a systems lens to evaluate trade-offs from pest management decisions. For example, chemical weed control can be used by farmers to facilitate adoption of conservation practices such as reduced tillage or cover crops, which in turn can improve soil conservation, increase soil carbon and reduce energy use and greenhouse gas emissions.
- This report presents data on chemical use and pest management practices from USDA surveys over the period 1990–2018. These data are valuable to illustrate the specific pest management challenges facing different crops, but due to the intermittent schedule of data collection and lack of a clear change over time, do not illustrate clear trends.
- Extensive scientific literature exists on specific chemicals and management practices, as well as evaluations of how management changes over time with the introduction of new pesticides and pest management practices. We draw from a fraction of that literature to better understand how environmental impact has changed over time.
- All sectors of the value chain can work together to advance responsible pest management through collective action. Changes will be most effective at reducing impacts when done in coordination among farmers within a broader community and their support networks. Pest management must become a collaborative effort.

1. Introduction

Field to Market works to advance sustainable agriculture in the United States by developing tools and programs for the supply chain to measure, monitor and improve on the environmental outcomes of crop production. Eight environmental outcomes have been identified as key impacts of concern across all stakeholder groups and metrics have been adopted to measure the current impact and track changes over time for: Biodiversity, Energy Use, Greenhouse Gas Emissions, Irrigation Water Use, Land Use, Soil Carbon, Soil Conservation and Water Quality[1]. These metrics are designed through a collaborative multi-stakeholder process to be science-based measures of environmental impacts [1,2]. Field to Market has also established national goals[2] for improvement in these environmental outcomes; responsible use of chemical pesticides is a key consideration for achieving those goals.

Field to Market defines responsible pest management as systems that ensure successful pest control with no adverse effects on human health, while optimizing crop yield, crop quality, and environmental protection and minimizing effects on biodiversity. Four of Field to Market's current metrics consider pest management as an important component of environmental impact, either for resource use efficiency or risk to ecosystems and human health. Energy use and greenhouse gas emissions are measured through efficiency metrics; farmer scores are affected by the number and type of chemical applications which are used to calculate the energy used and carbon dioxide (CO_2) released from the manufacturing of chemicals and applying chemicals to the field. Separately, adoption of Integrated Pest Management (IPM) is a factor in the metrics used to measure biodiversity and water quality.

Pest management and sustainable agriculture further intersect in farm management decision making that influences other aspects of the sustainability metrics. For example, chemical weed control can help farmers simplify management, reduce costs and improve efficiencies [3]. It can also facilitate farmer adoption of conservation practices such as reduced or no-tillage and planting cover crops. Adoption of genetically engineered (GE) herbicide tolerant soybeans, for example, has enabled increases of 10% in conservation tillage and 20% in no-tillage, compared to what would otherwise have occurred [4,5].

> Responsible pest management is not only about *what* methods are used, but also *how* and *when* they are used, and *why* farmers make the pest the management decisions they do.

A key component of sustainable agriculture is effective management of weeds, pests and diseases to minimize yield losses while also minimizing risks to the environment associated with pest management activities. Responsible pest management is not only about *what* methods are used, but also *how* and *when* they are used, and *why* farmers make the pest management decisions they do. In recent years, greater public concerns about chemical pesticide use in agriculture have led to increased attention to direct and indirect exposure (e.g. pesticide residues in food) and their potential human health impacts as well as environmental implications for water resources and biodiversity [6]. Urgency around protection of biodiversity has increased with recent reports indicating a widespread loss of biodiversity globally, some of which can be attributed to increases in chemical pesticide use since

[1] www.fieldtomarket.org/our-program/sustainability-metrics

[2] https://fieldtomarket.org/the-alliance/

the middle of the 20th century [7,8]. In 2018, a task force was convened to explore Field to Market's current consideration of pesticides and discuss additional action that the supply chain could take to protect biodiversity and water resources in U.S. agricultural landscapes.

One request from the task force was for a science-based assessment of trends over time in pest management across the crops in the Field to Market program, to help inform supply chain projects working to achieve improvements in environmental outcomes. We consulted with experts and the scientific literature to better understand the historical trends and drivers of agricultural pest management. We use publicly available data from U.S. government surveys of farmers to present several indicators illustrating pesticide use and pest management trends for individual crops. Finally, we provide insight into the opportunities available to organizations across the full agricultural value chain to reduce the environmental impacts of pest management.

2. Background: Pest Management in U.S. Agriculture

Pest management refers to the full suite of practices that farmers may use to identify and combat the threats that weeds, diseases, insects and other pests pose to crop productivity and quality. These include cultural practices such as using crop rotation to interrupt disease and pest reproductive cycles, mechanical strategies that physically interrupt or destroy pests, or chemical interventions using pesticides.

Pesticides include herbicides, designed to kill weeds, insecticides which act on insects, fungicides which control fungal diseases, bactericides which control bacterial diseases, and nematicides which act on nematodes. Pesticide products include active ingredients which function in controlling the target pest. Active ingredients include both synthetic and naturally occurring chemical compounds. Pesticides approved for organic production typically are limited to those with naturally occurring active ingredients.

Chemical pesticides entered widespread use after the insecticidal properties of organochlorides were discovered in the 1940s. Products such as DDT, aldrin, chlordane, and others were found to be very successful in controlling arthropod-borne disease and agricultural pests and were rapidly adopted. The scientific community then began reporting findings on how widespread use of these new insecticides was harming biodiversity. Problems included pest insects developing resistance to the chemicals, harm to populations of beneficial and non-target organisms, insecticide residues found on food, hazards to workers handling the insecticide and exposure of people, livestock and wildlife [9]. As a result of the scientific findings, agricultural uses of DDT were canceled in 1970, and the use of the rest of the organochloride pesticides followed a similar fate.

As newer pesticides have been approved, research has shown that even when used according to all rules and regulations they can persist in the atmosphere, soils, ground and surface waters, with long-term impacts to biodiversity emerging in areas of widespread and long-term use [10,11]. The contamination of water resources by pesticides near agricultural land is an ever-present concern for water managers; surveys have shown that at times pesticide concentrations can exceed levels considered safe for soil and aquatic organisms [12]. Pesticides and their residue chemical compounds that persist in the environment are usually found in mixtures [13–16] and the concentration fluctuates throughout the year; this makes it difficult to assess potential health and ecological consequences [17,18,19].

This section provides background on chemical pesticide use and what is known about the change over time in agricultural systems, the environmental impacts, and the evolution of pesticide resistance. We also review how pesticides are regulated, what is meant by Integrated Pest Management (IPM) and how community strategies can support farmers in adopting practices to reduce the environmental impacts of pest management.

2.1 Why and How Farmers Use Chemical Pesticides

Farmers have always had to cope with insect, disease, weed and other pest challenges to production by staying informed on emerging pest threats and effective management strategies. Beginning in the second half of the 20th century, those management strategies increasingly included application of chemical pesticides [3]. Research and development have led to the introduction of pesticides that are effective at targeting specific pests while being cost and labor efficient. In addition to controlling crop pests, some chemical pesticides have assisted farmers in adopting conservation practices that reduce tillage and incorporate winter cover crops, leading to reductions in soil erosion and improvements in water quality and soil health [20].

Many factors contribute to the decision about whether, how, when and where to apply chemical pesticides. Every product labelled for use in the U.S. comes with detailed instructions on safe application and storage, based on risk information reviewed during the product registration process (see sidebar 1). All pesticide applicators, including farmers, must receive training, become certified to handle the chemicals, and abide by stringent, legally-enforceable requirements specified on the product label, including chemical application rates and timing and limitations on the number of applications per year. Farmer pesticide use decisions are supported by a network of Extension specialists and advisors employed by the U.S. Land-Grant University system and private-sector crop advisors. Private-sector advisors include independent crop consultants, who are hired and compensated for advice, as well as employees of pesticide manufacturers, distributors and retailers.

2.2 How Chemical Safety is Evaluated

In the United States, pesticide use is regulated to ensure the benefits outweigh the risks to non-target organisms including humans, plants and animals (see sidebar 1). After regulatory approval at the federal and state levels, these products are made available to farmers throughout the country via local retail companies who also may serve as one source of advice to farmers on many agronomic topics including pest management [21].

Chemical pesticides are designed to kill or otherwise disrupt pests and thus are toxic by design. When evaluating the safety of chemical pesticides, scientists and regulators use a risk-based framework that accounts for two primary factors:

1. The likelihood and frequency of *exposure* to the chemical, and
2. The *toxicity* of the specific chemical being evaluated.

A chemical may pose low risk even though it is highly toxic due to a low likelihood of exposure because only small quantities are allowed, or the application methods limit contact with the product. Conversely, a chemical with low toxicity but a higher possibility of exposure may pose a greater risk and require different rules to regulate its use. Pesticide toxicity is also evaluated to determine the extent to which compounds pose an *acute* (immediate, high level exposure) or *chronic* (long term, low level exposure) risk to human health or the environment. This is based in part on how long the chemical persists in the environment; if it degrades quickly to non-harmful compounds, the overall risk will be lower. Human health risks are evaluated separately in different sub-populations. For example, agricultural pesticide applicators may have a higher risk profile than people living in the communities adjacent to farmland. Risks to children and pregnant women are considered greater due to differences in metabolism, system development and behaviors that can lead to heightened susceptibility.

The complexity of toxicology and categorizing risk can make it difficult for consumers to assess the potential harm to their health or the environment from agricultural chemical use. This situation

> To increase consumer confidence in the food system, it is important for food companies, farmers and the full value chain to provide transparency and communicate efforts to ensure responsible pest management that minimizes the risk of harm to consumers, biodiversity, water quality and the environment arising from chemical use.

can become more charged over time when consumers lose confidence in the scientists and regulatory agencies responsible for conducting the risk evaluations and setting regulations [22,23]. Misunderstanding and mistrust can grow when appropriate information is not readily available and understandable by a non-technical audience. Simply presenting scientific facts to the non-scientific public is generally ineffective if those facts contradict previously held beliefs [24].

Increasingly, it is peer communities, not scientists, that are influencing consumer beliefs about agriculture. To increase consumer confidence in the food system, it is important for food companies, farmers and the full value chain to provide transparency and communicate efforts to ensure responsible pest management that minimizes the risk of harm to consumers, biodiversity, water quality and the environment arising from chemical use [25].

Sidebar 1

How Pesticides Are Regulated in the United States

In the United States, the Environmental Protection Agency (EPA) is assigned authority for registering or reregistering pesticides under the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA). FIFRA governs the sale, distribution, and use of pesticides and plant-incorporated pesticides (PIPs) such as genetically engineered (GE) crops that produce the *Bacillus thuringiensis* (Bt) insecticidal proteins. EPA also partners with state agencies to register pesticides, assure compliance and investigate problems. In addition, individual states may also have registration processes that further restrict uses. Pesticides are among the most highly regulated products in the United States [26].

Pesticides must be registered with the EPA before they can be sold to farmers. In an effort to balance benefits and risks, a new pesticide must not cause "unreasonable adverse effects on the environment" (7 U.S.C. § 136a(c)(5)), defined as:

- "Any unreasonable risk to man or the environment, taking into account the economic, social and environmental costs and benefits of the use of any pesticide" (7 U.S.C. § 136(bb)).
- "A human dietary risk from residues that result from a use of a pesticide in or on any food" unless the EPA determines that "there is a reasonable certainty that no harm will result from aggregate exposure to the pesticide chemical residue" (21 U.S.C. § 346a).

The organization seeking to register a pesticide is responsible for providing the scientific evidence of its effectiveness [26]. This consists of data on product toxicology, biology, chemistry, environmental fate, field trials, and impact on selected non-target species [27]. Pesticide discovery and commercialization average costs increased from $13M in 1995 to $33M by 2010–2014 [28]. A minor portion of registration costs go toward statutory fees; most of the costs are for documentation, efficacy tests, and field trials. When research and development costs are included, companies have reported a cost of up to $286M to bring a new pesticide to market. It also takes substantial time for a newly discovered chemical product to come to market — increasing from an average of 8.3 years in 1995 to 11.3 years by 2010–2014 [28].

The Food Quality Protection Act (FQPA), a 1996 amendment to FIFRA, established a review cycle in which pesticide registrations must be reevaluated every 15 years. One purpose of the review is to evaluate scientific developments and pesticide practices to ensure that the pesticide still meets FIFRA safety standards [29]. The changing regulatory landscape for pesticides increasingly favors products that can pass more stringent environmental and toxicological requirements, resulting in the cancellation of hundreds of older pesticides over the past few decades [30].

Under the Federal Food, Drug and Cosmetics Act (FFDCA), EPA establishes maximum legally permissible levels for pesticide residues in raw agricultural commodities and processed foods, enforced by the Food and Drug Administration (FDA. When approving a pesticide, the EPA must either establish an allowable concentration of the pesticide (tolerance) in the processed food or commodity, or exempt the pesticide from the tolerance requirement [26]. PIPs and foliar Bt insecticides are examples of many pesticides that have been granted exemptions from the tolerance

(Continued on page 7)

Sidebar 1 — Continued

How Pesticides Are Regulated in the United States – *Continued*

requirement. The tolerance level is based on the daily oral dose of a pesticide that is likely to result in no ill effects during a lifetime; uncertainty factors are applied to account for the fact that pesticide tests are conducted in animals and for potential differences between humans [31]. Commonly, the EPA applies a 10X (ten-fold) factor for each uncertainty factor, bringing the total factor to 100X. Sometimes, an additional 10X factor is applied to account for childhood susceptibility (for a 1000X total factor).

In an effort to reduce overall risk of pesticides to human health, non-target organisms, and groundwater, the Conventional Reduced Risk Pesticide (CRRP) program expedites the registration process for qualifying pesticides deemed as lower risk [29,32]. The reduced risk designation must be granted when the pesticide is first registered and is based on comparison to registered conventional pesticides for a specific crop or usage. This results in what might appear to be an inconsistent reduced risk designation across crops; for example, the herbicide glyphosate has reduced risk designation for glyphosate-tolerant corn, sugar beets, and canola, but not for other crops [33]. Reduced risk designations might differ since for some crops the alternatives have a higher risk potential. Although more than 50 reduced-risk pesticides have been registered, their usage in agricultural applications, as measured by the share of agricultural acres treated with these pesticides, is dominated by two pesticides: glyphosate (75% of CRRP-treated acreage) and Bt crops (20% of CRRP-treated acreage) [34]. EPA also maintains a list of inert, non-toxic ingredients that qualify as minimal risk [35].

Pesticide registration procedures established by EPA have not been without criticism. The CRRP program has raised concerns about the quality and timeliness of EPA's decisions, and inadequate applications submitted by industry applicants [36]. Other analysts have written about flaws in the conditional registration exemptions allowed by FIFRA section 3(c)(7) and granted by the EPA [37–39]. EPA reported ways in which it addressed the recommendations from the Government Accountability Office [40]. Conditional registrations are meant to be used in limited circumstances as a temporary measure when EPA has asked for additional data after a registration package was submitted and the additional data requirement could not have been anticipated by the registrant. Proponents of the conditional registration process argue that it allows for new technologies to reach the marketplace faster, while opponents argue that the process allows for commercialization of pesticides for which safety has not been completely verified [37], and that conditional registrations violate the original purpose of FIFRA [39]. One example is the neonicotinoid insecticides, which have received conditional registrations that have been renewed periodically, but the full EPA registration process has not been completed [41].

2.3 How Has Agricultural Chemical Use Changed Over Time

Agricultural chemical use expanded significantly in the latter half of the 20th century as scientists discovered and developed new products targeted to specific pest species. A USDA Economic Research Service report [3] assessed pesticide use trends from 1960 through 2008 using information collected from farmer surveys. Analyzing data for several hundred pesticide active ingredients, they found that pesticide use over five decades contributed to increased yields and higher quality crops while reducing labor and machinery costs for weed control. The active ingredients changed substantially over that period as new products were developed and approved. Many of the changes in pesticide use were driven by technical improvements in chemistry, adoption of Integrated Pest Management (IPM) strategies, development of GE crops, adoption of conservation practices by farmers and changing pesticide regulations. Changes in crop mixes and acreage across the country also drove changes in the types and amounts of pesticides used.

Overall, chemical pesticide use increased from 1960 to the early 1980s, driven primarily by new herbicides on the market.

The broad adoption of GE herbicide tolerant crops initially led to declines in herbicide use, however in recent years herbicide use has increased as weeds have evolved resistance to widespread use of specific chemical active ingredients.

This increase is measured in the quantity of total amount of chemical applied [42] and in the proportion of acres receiving chemical applications. This reflects, in part, that the herbicides were initially more effective and less costly than the labor, equipment and fuel needed for mechanical weed control. Since the early 1980s, fluctuations in the total amount of pesticide applied have largely reflected planted crop acreage, with some additional trends apparent as new pesticides are introduced that have different effective application rates. In the mid-1990s, the introduction of the first herbicide tolerant GE crops — cotton, corn and soybean — led to increases in use of the herbicides that could control weeds without killing the crop. This did not impact the acreage treated with herbicide, which remained constant, but it did change the mix of chemicals applied, which became dominated by glyphosate and glufosinate [43]. By 2017, 90% of the acres planted to corn, cotton, soybeans, sugar beets, and canola produced in the United States were cultivated using herbicide tolerant GE varieties. The broad adoption of GE herbicide tolerant crops initially led to declines in herbicide use, however in recent years herbicide use has increased as weeds have evolved resistance to widespread use of specific chemical active ingredients. These resistant weeds are typically managed by using more frequent chemical treatments and a wider range of chemical active ingredients. In the period from 2010-2014, this resulted in herbicide application rates increasing by more than 20% for soybeans, wheat, cotton and corn [44]. Farmers are seeking solutions to this resistance challenge; as one example, the emergence of glyphosate resistant weeds has recently led to increasing adoption of a new GE soybean variety introduced in 2017 with a tolerance for dicamba, an older herbicide [45]. While this provides an alternative approach to targets weeds that have developed resistance to other herbicides, dicamba has a high potential for drift and consequences of dicamba drifting from the target field and causing damage to neighboring crop fields and other plants [46] are raising concerns in farming communities.

Over the same period, insecticide use fluctuated due to changes in product availability and the episodic nature of pest outbreaks where there is greater risk of damage in certain years due to environmental factors such as weather conditions favorable for certain species. Crops genetically engineered to produce Bt proteins that are toxic to specific insect pests were introduced for corn and cotton in the mid 1990's and by 2017, these Bt varieties were planted on approximately 80% of corn and cotton acres. This initially led to a decline in insecticide use which was reversed following the introduction and widespread adoption of insecticidal seed treatments in 2004 [47]. Recent studies have documented that widespread use of neonicotinoid seed treatments has resulted in an increase in the toxic load of insecticide use in the United States since 1997, as they must be applied at planting, as insurance

The trends in herbicides and insecticides have been well documented as they impact the crops grown over the largest areas of farmland in the U.S. — corn, cotton, soybeans and wheat. Fungicide use is more prevalent on fruit and vegetable acres, although they are also used to combat diseases on potatoes, peanuts, wheat and other crops as needed. Other pesticide applications including soil fumigants, defoliants, desiccants, harvest aids and plant growth regulators, are used frequently on cotton and potatoes, which together accounted for 82% of their use in 2008 [3,44]. We address some of these trends in the crop specific sections later in this report.

against pest damage rather than in response to identified specific pest risk in a given year [48].

Several large-scale trends in agricultural systems have followed from developments in seed and chemical technology. Effective chemical weed control is generally less expensive than alternatives which require more labor and this has been a driving force behind reduction in demand for farm labor and increase in farm size [49]. In addition, chemical weed control has helped many farmers reduce the frequency and intensity of tillage and incorporate cover crops in their rotations, important drivers of reduced soil erosion over the past several decades. Reducing soil erosion benefits water quality by reducing sediment and nutrient losses to streams, and also can improve soil health and the ability of soil to accumulate and store carbon.

It is important to note that these trends reflect changes for farmers across their whole operation that impact far more than just pest management decisions — everything from how the farm financing and business model is set up to what equipment is purchased. These structural features are difficult and costly to change; there is a level of inertia built into current cropping systems and the pesticide programs used by farmers. Calls for individual farmers to stop using a specific chemical, which many might consider a simple individual choice, in fact require a more complex response involving a community-wide level of change. For example, the seeds available for sale, the technological tools available for scouting, and access and rules for financial assistance and crop insurance all may limit farmers' options. The farming and agribusiness communities need to work together to devise alternate pest management solutions to respond to public concerns about biodiversity loss and environmental impacts from current agricultural chemical use.

The farming and agribusiness communities need to work together to devise alternate pest management solutions to respond to public concerns about biodiversity loss and environmental impacts from current agricultural chemical use.

2.4 How Have Risks from Agricultural Chemical Use Changed Over Time

Although there are thousands of studies evaluating the risks of specific chemical ingredients to specific populations in specific ways, there is no universally accepted method for aggregating across risks, chemicals, active ingredients, rates and modes of applications and populations to create a composite measure of pesticide risk over time. Research on pesticide trends fall into two broad categories: assessment of the volumes of chemical applied and number of applications, or assessments of how specific risks have changed over time.

An example of a study looking at changing risks over time focused on the mammalian toxicity of various herbicide mixes used on several major crops and calculated a "hazard quotient" for acute and chronic toxicity [50]. While chronic toxicity has slightly increased due to herbicide applications on corn and cotton from 1990–2014, there were large declines in acute toxicity. Both chronic and acute toxicity of herbicides used in soybeans declined over the same time period. In wheat, the chronic toxicity of herbicide use has decreased while the acute toxicity has remained steady or increased. These changes over time reflect both the changing mix of chemicals used along with changes in the application frequency and amounts. The study also found that herbicide use intensity — the number and area of applications — increased for all crops over the same time period. The study did not evaluate other changes in environmental impacts resulting from herbicide use.

A second example of the risks of pesticides changing over time is the emerging understanding of the impact of neonicotinoid insecticides when adopted broadly across the landscape over many years. Neonicotinoids have become widely adopted since their introduction in the 1990s because they are selectively more toxic to insects than to vertebrates, and so pose low risks to human health. They also offer advantages to farmers in their flexibility of use and high efficacy at controlling pest insects. Although they are used at far lower rates than older classes of insecticides (e.g. pyrethroids), they are also more toxic to insects, are water soluble, and are used more broadly. These characteristics have led to environmental concerns as usage has become widespread [51].

As neonicotinoid modes of action and fate in the environment have been studied, scientists have raised concerns about how widespread use may be contributing to the global decline of biodiversity [7]. A study to evaluate impacts on non-target insect species [8] using an approach called Acute Insecticide Toxicity Loading (AITL) found that the increase in use of neonicotinoids has resulted in an increase in the oral and contact toxicity for non-target insects in the period 1992-2014. Recent research has also connected declines in insect populations associated with neonicotinoids to declines in insectivorous bird populations [11], impacts on wildlife exposed to treated seeds [52] including impacts on deer populations [53], aquatic biodiversity and fish populations [10] and potential risks to the health of birds that consume neonicotinoid treated seeds [54].

Widespread pesticide use itself can lead to public concerns about unintended consequences, especially when the broader context about the benefits of pesticides to farmers and the food system, and the alternatives to chemical use, are not also communicated to the public.

These studies illustrate the complexity of assessing multiple human health and environmental risk factors from agricultural chemical applications, and the importance of considering all dimensions of risk in the regulation of chemicals. One important factor is how the broad availability and economic advantage of certain cropping systems and the associated chemical use can create a more uniform, homogeneous landscape, which amplifies the harmful impacts on ecosystems which are not necessarily captured in initial risk evaluations [55]. In other words, even a small amount of pesticide on each acre treated can lead to a substantial environmental load when spread across more than 100 million acres each year.

There is a need for ongoing research to understand the impacts of chemical use over time, particularly for the pesticides that become adopted widely over the landscape. That widespread use itself can lead to public



concerns about unintended consequences, especially when the broader context about the benefits of pesticides to farmers and the food system, and the alternatives to chemical use, are not also communicated to the public. Work by scientists, advisors and extension agents to help devise and implement management strategies is important both to mitigate potential harm and communicate with the public about safeguards to protect human health and biodiversity. The EPA review process for re-evaluation of approved chemicals is also critical to ensure public confidence that new information about risks will be factored into continuing use and rules governing chemical applications in agriculture.

Aside from the direct human and environmental health impacts considered in pesticide regulation, an additional multi-faceted risk exists — the evolution of pest resistance. Pesticide resistance is the evolution of decreased susceptibility to a pesticide by a pest population in response to the repeated use of a chemical active ingredient that was previously effective at controlling the pest. Resistance develops when a population is repeatedly exposed to the same chemical or mode of action, as has become increasingly common. Individual pests that survive the first application and reproduce pass the genetic traits that allowed them to survive the pesticide application to the next generation, and those traits become more prevalent in the population over time.

As a result, pesticide resistance is becoming a significant farm management challenge that threatens crop production and farmer livelihoods. Pesticide resistance is an environmental outcome of concern that Field to Market member organizations are well placed to help understand and mitigate through program development and field-level projects.

2.5 The Growing Challenge of Pesticide Resistance

Pesticide resistance is becoming a significant farm management challenge that threatens crop production and farmer livelihoods.

The change in chemical herbicide active ingredients applied on U.S. agricultural land has been widely regarded as a positive substitution of less toxic chemicals for the more toxic products previously applied [20]. However, concerns are increasing following the evolution of herbicide-resistant weeds and insecticide-resistant pests. When pests evolve a resistance to a class of pesticide — whether a chemical or a plant incorporated pesticide — they can no longer be controlled by typical treatments; thus, farmers have to seek out alternative management approaches. A report by USDA [44] documented an increase in herbicide use from 2010–2014 for corn, soybeans, wheat and cotton due to multiple weed species developing resistance to commonly applied herbicides, leading to more applications of additional chemicals. This challenge continues to escalate as weeds are developing resistance to multiple herbicide active ingredients. Once a population has evolved this resistance, the trait is passed on to the next generation and spread over large regions, impacting all farmers.

Pesticide resistance has become more widespread as cropping systems and the chemicals applied to control pests have become more uniform [56]. More than 250 weed species have evolved resistance to at least one herbicide. Of the 26 different herbicidal modes of action known, weeds have successfully developed resistance to 23, with resistance to over 150 individual herbicides as a result [57]. Cases where individual weed species are resistant to as many as six different herbicide modes of action have also been discovered [58].

Research on farmer perceptions of herbicide resistance have found that they view the problem as resulting from how other individual farmers have applied the chemicals, and that the most effective solution is new herbicides [59]. Historically, farmers could rely on discovery of new herbicide modes of action targeting a different vulnerability of the weeds.

Unfortunately, no new herbicidal modes of action have been discovered in the past 30 years, and thus alternative approaches to weed management are necessary [60]. Farmers are more likely to adopt integrated pest management for weed control after first-hand experience with herbicide resistant weeds on their own fields [61]. Looking forward, researchers [60] emphasize the need for continued research and development of management techniques that are based on a better understanding of both weed biology and ecology, and point to trends in precision agriculture, crop breeding and new biopesticide approaches (see sidebar 2) as areas of promising research to develop alternative weed control.

Pesticide resistance is not limited to weeds. The western corn rootworm, corn earworm, western bean cutworm and European corn borer have all evolved resistance to *Bacillus thuringiensis* (Bt), the widely adopted plant-incorporated pesticide in GE corn and cotton varieties [62]. Recently, resistance to neonicotinoids has been found in tobacco thrips, an insect pest that impacts cotton, in areas where seed-treatments are widespread and thus insects have received repeated exposure [63]. Some scientists have argued that pest susceptibility to chemical control should be treated as a natural resource that can be depleted [64,65]. Framed in this manner, the conservation of pesticide effectiveness is an important motivation for adoption of Integrated Pest Management strategies.

Awareness and concern about resistance problems have been growing among farming communities, and best management practices to avoid and combat the problem are well understood [66]; however, adoption of those management practices has been low [67]. While the practices are well understood, such as rotating crops, not using Bt hybrids or seed treatments where pest pressures are low and rotating chemical modes of action (including different Bt hybrids targeting the same pest, where available), adapting the farm management system to the changes may require greater cost and effort in the short term compared to chemical interventions [68]. For this to be a viable option for farmers, companies must make options available, including seeds that do not incorporate pesticides, through Bt genetics or seed treatments, so that farmers have access to cost-effective options and opportunities to employ IPM practices. Resources to help farmers determine whether different chemical products target differing modes of action would also assist in combating resistance.

All of these strategies are more effective when they are adopted area-wide — weed seeds, diseases and pests spread across fields in a region regardless of who is farming them. Therefore, to reduce the instances of pesticide resistance, it is crucial to look beyond the chemicals that can be used in *suppression* of the pest species and include discussions of the management practices that can be used in *prevention*, *avoidance*, and *monitoring* of the specific pest threat. These are described in greater detail in the next section.

2.6 Integrated Pest Management

Integrated Pest Management (IPM) is an approach to managing pests in a way that minimizes economic, health, and environmental risks. IPM's initial development can be partly attributed to the negative impacts from excessive use of certain insecticides in the mid-20th century [77–79]. Early researchers found that pest resurgence — when pest populations rebound to equal or greater numbers after a chemical treatment — was a consequence of indiscriminate insecticide applications. California entomologists developed the notion of "supervised control", in which entomologists monitor populations of both insect pests and natural enemies, and recommend insecticide applications only when pest pressure is observed to warrant treatment, rather than based on the calendar or as an insurance measure [80]. Entomologists went a step further to develop "integrated control", an approach in which biological, chemical and other methods are used together to manage insect pests [9,81,82].

Sidebar 2

Biopesticides

Biopesticides are developed from animal, plant, bacteria, and mineral materials and are an emerging alternative to conventional pesticides [69, 70, 71]. For example, limonene (a citrus extract) [72] and sodium bicarbonate (baking soda) [73] have pesticidal properties and are registered as biopesticides. The category also includes pheromones, attractants, and repellents [70,74]. A biopesticide is different from biological control where a living organism is released to actively seek out and eliminate a pest. Biopesticides must be registered by the EPA, while biological controls are not.

In the mid-nineties, the EPA established the Biopesticides and Pollution Prevention Division to facilitate the registration of biopesticides and promote the use of safer pesticides. It is faster and simpler to register biopesticides than conventional pesticides; on average, it takes less than a year to register a biopesticide, versus more than three years for conventional pesticides [71].

Depending on the active ingredient, biopesticides are nested into three main categories:

- **Biochemical pesticides** include naturally occurring substances or their synthetic equivalent and have low toxicity to humans and the environment. Unlike conventional pesticides that directly kill or inactivate the target pest, biochemical pesticides kill pests by non-toxic mechanisms, such as suffocation, desiccation, or abrasion [75]. Other biochemicals, such as pheromones, control target pests by disrupting mating cycles.
- **Microbial pesticides** include products where the active ingredients are microorganisms such as bacteria, viruses, and fungi that have a pesticidal effect. Common modes of action consist of competition, inhibition, and using the target pest as a growth medium [75]. The most common microbial pesticide is the *Bacillus thuringiensis* (Bt) bacterium, a soil-borne organism that produces a protein which is toxic to some insect larvae when ingested. There are several Bt strains, the proteins of each are toxic to a specific insect larvae type.
- **Plant-incorporated protectants** (PIPs) are biopesticides produced by genetically engineered (GE) crop plants. Pests must feed on living crops producing PIPs to be exposed. To date, the most widely used, commercially available PIPs are insecticidal proteins produced by the Bt bacterium. There are also PIPs (dsRNA) to suppress the plum pox virus in stonefruits, leafroll virus in potatoes and the papaya ringspot virus. The EPA regulates the pesticidal products and the genetic material introduced into the plant, but not the plant itself. As of 2018, there are 32 active PIPs registrations: corn (13), cotton (9), soybean (5), and potato (3) dominate the list, the remaining two registrations are for plum and papaya [33].

The use of PIP crops is high — millions of acres are planted with PIP cotton, corn and soybeans every season as these traits have become almost universal in corn and cotton high-yielding hybrid seeds available to farmers. As a result there are several insect pests that have already developed resistance to Bt toxins. However, biochemical and microbial pesticide usage is low. Latest estimates show they only have a 4–6% share of the pesticide market [69]. Some of the barriers preventing higher adoption of biopesticides include farmer's lack of familiarity with biopesticide products and perception of risk and effectiveness [76].

IPM as it is currently understood took shape in the early 1970s, when pest management came to include all types of pests (insects, mites, nematodes, weeds and other pathogens) and was regarded as a multidisciplinary endeavor [77,83–85]. Over the past several decades, IPM has become an umbrella under which research and extension efforts can be organized and communicated to farmers.

With the expectation that increased IPM adoption would lead to decreased pesticide use, the USDA launched the National IPM Initiative in 1993 [86], with a goal to manage 75% of crop acreage under IPM practices by the year 2000 [87]. The USDA encouraged growers to use the "PAMS" strategy — Prevention, Avoidance, Monitoring, and Suppression [88].

- **Prevention** is keeping pests from infesting a field; it emphasizes sanitation practices such as cleaning tillage and harvest equipment after completing work at each field and protecting habitats for pest predators.
- **Avoidance** is using sound cultural practices to reduce pest impacts when they are already present. Avoidance practices include planning crop rotations, adjusting crop planting or harvest dates, and choosing crop varieties resistant to a specific pest. Prevention and avoidance may overlap as they both keep potential pests away from susceptible crops.
- **Monitoring** refers to the use of scouting, soil or plant tissue testing, weather data, and record keeping; all these tactics become the basis of suppression efforts. Effective pest monitoring requires correct identification of pests and pest predators in all life stages.
- **Suppression** tactics are applied when prevention and avoidance strategies have failed, and monitoring indicates that action is needed to avoid economic losses. Chemical pesticide applications are one suppression tactic; other practices include tillage, trap crops, cover crops, residue management, and applying biopesticides (see sidebar 2), among others.

> For a farmer, IPM is a complex system that requires managing multiple pests at the same time, frequent monitoring of pests and their natural enemies, establishing economic or pest population thresholds before applying pesticides, and integrating several suppressive tactics.

IPM practice adoption — defined as the percentage of acreage where at least one farming practice in three of the four PAMS categories was adopted — increased from approximately 40% in 1994 to 70% in 2000 on all U.S. cropland; however, this did not materially impact pesticide use trends. Total pesticide use (as measured by pounds of active ingredient) increased by approximately 4% during the same time period [89]. This indicates that meeting the definition of adoption does not necessarily reflect adoption of a comprehensive PAMS approach. In particular, the incorporation into seeds of pesticides or traits designed to be used with pesticides leads to widespread use of chemicals as a risk mitigation measure, rather than as a response to a specific identified threat as is called for in IPM. As such seeds are more profitable for sales companies, certain retail policies may encourage growers to purchase them by offering incentives that are not offered for untreated seeds. Research has found that, in some instances, the higher cost of purchasing a treated seed outweighs the benefits to farmers [90,91].

The current IPM federal initiative was launched in 2003 [92], with the main goal "to increase adoption, implementation and efficiency of effective, economical and safe pest management practices, and to develop new practices where needed" [93]. Effective adoption of IPM requires more than just one action, but rather a concerted effort and changes to how a farmer manages a crop, industry support to provide the seed options required, and technical support to identify and adopt appropriate measures.

For a farmer, IPM is a complex system that requires managing multiple pests at the same time, frequent monitoring of pests and their natural enemies, establishing economic or pest population thresholds before applying pesticides, and integrating several suppressive tactics [78]. Monitoring or sampling pest populations to determine need and timing for pesticide applications is one of the most widely adopted tactics. In practice, the lack of integration has been one of IPM's main criticisms [78,94,95]; researchers have noted that IPM as it is applied in practice still emphasizes pesticide-based programs [66,94–97], in which scale and convenience have facilitated the adoption of prophylactic pest control as a form of insurance [98].

Some of the obstacles farmers face in implementing a truly integrative approach to pest management [78,99] include:

- **Financial:** Perception of lack of profit in the short-term, too time consuming, and higher labor costs compared to chemical control; limited evidence and communication of the long-term cost savings associated with IPM.
- **Technical:** Lack of simple pest monitoring methods and devices, unidentified economic injury thresholds, limited availability of selective pesticides, insufficiently trained personnel to conduct field visits and monitoring.
- **Behavioral:** Crop producer resistance to change, perceived risk, low confidence in IPM methods, and familiarity with available chemical control options.
- **Industrial:** Producer behavior and satisfaction with status-quo pesticide options may be influenced by marketing strategies and the number and accessibility of chemical sales personnel compared to university Extension or other public institution staff.
- **Educational:** Growers may not have access to adequate information to confidently make agronomically, economically and environmentally sound decisions. IPM is an interdisciplinary approach and needs the participation of agronomists, economists, educators, and entomologists, among others to make the right information available and understandable.
- **Complexity:** An IPM program needs an in-depth view of a grower's entire production system, including biological, technological, commercial, and economic aspects.
- **Lack of incentives:** Producers might not test IPM programs until an incentive is provided. Even then, IPM methods must compete with chemical control methods that producers and their agronomic advisors from industry are familiar with, produce visible results, and reach high levels of predictable pest control.

Community-wide collective discussion and action to mitigate difficult pesticide resistance challenges would increase the effectiveness of individual farmer actions.

Farmers are more likely to adopt new management practices when they are time-saving, convenient and profitable, as well as simple and flexible. This trend is nearly universal and explains the rise of approaches such as GE crops and insecticide-treated seeds. Both require no special equipment to apply and are relatively simple and safe for operators. Where IPM practices can be enabled with new technology such as remote sensing to assist with scouting of fields for damage, or use of community-wide databases of damage reports, or real-time pest identification tools, greater adoption will become more feasible. A key to increasing adoption will be demonstrations of on-farm efficacy, using commercial-scale field experiments that test IPM versus preventative pest management approaches. In addition to individual action, community-wide collective discussion and action to mitigate difficult pesticide resistance challenges would increase the effectiveness of individual farmer actions [65,100].

2.7 Community Strategies for Responsible Pest Management

Farm management in the U.S. has traditionally been viewed as individualistic — each individual farmer is and should be free to make the decisions most appropriate to their operations and goals [68]. However, insects, weeds and diseases do not recognize property boundaries, and thus each individual farmer decision regarding pest management will necessarily impact their neighbors and community. This has become an important consideration as problems with pesticide resistance have increased, and requires a coordinated response by farmers, their advisors, and supporting organizations. In particular, businesses working with and advising farmers should ensure that they offer a range of products and services that are compatible with IPM.

It is appropriate to consider collective action by farming communities when it comes to managing pest damage and pesticide resistance — IPM applied on a community-wide scale. Pest susceptibility to chemical control can be treated as a collective natural resource that the whole community has an interest in preserving. Doing so requires community-wide adoption of pest management strategies that preserve the resource. Establishing partnerships and community groups to collectively evaluate pest threats and make decisions on management should be considered.

> Overcoming the obstacles to adopting IPM is something the entire agricultural value chain can support.

Such voluntary collective action has been effective for other natural resource concerns, but it requires incentives and support to bring communities together to identify appropriate solutions [100–102].

Farming communities shouldn't have to tackle the complex challenge of responsible pest management alone. Overcoming the obstacles to adopting IPM is something the entire agricultural value chain can support. Structural changes in the agricultural system can enable swift and influential agronomic changes that effectively manage pests without harming human health, the environment, or farmer livelihoods [103]. Investments can be made in advancing seed technology, developing technological support for IPM practice adoption, or supporting infrastructure to accommodate more diverse crop rotations. Sustainable farming that protects both farmer livelihoods and biodiversity will be enhanced by embracing IPM effectively.

3. Data and Methodology

Here we present USDA data on chemical use and IPM practices for nine crops in the Field to Market program focusing on the period from 1990–2018. Sufficient data were not available to conduct an analysis for alfalfa or sugar beets, the other two crops currently included in Field to Market programs. The primary indicator for responsible pest management is IPM practice adoption, and data on specific practice adoption — measured as the proportion of planted acres of the crop reporting use of a practice — are available from USDA for at least two years since 2000. We also present USDA data on pesticide use in volumes applied by chemical category; while we noted earlier that this measure is of limited value in understanding change in risk due to chemical use over time [8], it does help to illustrate the trends in management that are described for each crop. We also include data on crop yield and acreage in order to add context to discussions of pest management challenges. We highlight both common IPM practices as well as practices with relatively low adoption which have been identified by experts as important strategies for managing a particular pest management problem with that crop. Not all IPM practices will be relevant to all growers, or in all years.

Four data categories per crop were downloaded from the USDA National Agricultural Statistics Service (NASS) online platform: pounds of pesticide active ingredient applied (herbicides, insecticides, fungicides, and others, which includes soil fumigants and growth regulators); area planted in acres; yield per acre; and IPM practice adoption expressed in percent of area planted.

Note that data on pesticides and IPM practice are not collected for every crop in every year (Tables 1, 2). A matrix of data availability per year, state, crop, and data categories was created to exclude incomplete or insufficient sets of information. Within a given crop, pesticide amounts and acres planted with IPM practices are presented for a consistent set of states and years. The states included for each crop are listed in Appendix B.

> NASS chemical application data include only pesticides applied to a crop and do not include seed treatments.

For each pesticide type, the total quantities provided by NASS were selected for data after 1994. For data before 1994 the amounts for individual active ingredients by category were added together. The total quantities of pesticide active ingredient per category and year were divided by the corresponding total quantity of area planted per year to obtain pounds of active ingredient per acre. An average value by year was calculated for

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Barley														■								■						
Corn		■	■	■		■	■				■	■		■		■					■						■	
Cotton																		■								■		■
Peanuts										■					■									■				
Potato					■	■				■				■		■					■				■		■	
Rice											■													■			■	
Sorghum														■								■						
Soybean	■	■	■	■				■	■	■	■		■				■						■			■		■
Sugar Beet											■																	
Spring Wheat						■					■				■		■			■								■
Winter Wheat						■					■				■		■			■			■			■		■

Table 1: Years of chemical pesticide use data availability for each crop considered in the analysis.

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Barley					■							
Corn				■				■		■		
Cotton	■								■		■	
Peanuts							■					■
Potato				■				■		■		
Rice							■					
Sorghum					■							
Soybean						■			■		■	■
Sugar Beet												
Spring Wheat			■			■			■		■	
Winter Wheat			■			■			■		■	

Table 2: Years of IPM practice adoption data availability for each crop considered in the analysis.

crop yield. Note that the NASS chemical application data include only pesticides applied to a crop and do not include seed treatments — seeds coated with a chemical pesticide prior to planting. As discussed earlier in this report, seeds treated with neonicotinoid insecticides have become almost universal for some crops. While the volume of chemical product used in seed treatment is very small, data are not collected on the aggregate amount used across the landscape. When considering separate data on seed treatments, more extensive insecticide use — in terms of the number of applications and percentage of planted acres receiving a chemical treatment — since the early 2000s is clear for crops including corn, soybeans, cotton, and wheat [47].

IPM practice adoption was averaged by year, crop, and pest management strategy. Fourteen pest management strategy categories were defined for this analysis based on the Prevention, Avoidance, Monitoring, Suppression (PAMS) framework using the IPM definition developed by USDA [104]. The pest management practices available in the NASS data were mapped onto the fourteen broader categories (see Appendix C for full descriptions of the categories included here); not all 48 pest management practices in NASS were used in this analysis. A practice was considered as high adoption if greater than 40% of acres for the crop reported its use; the exception is potatoes, where overall IPM practice adoption is high, and the threshold was set to 60% of acres of the crop. Priorities for adoption were identified in consultation with national commodity organizations in discussion around the main pest management challenges, and the applicability and feasibility of specific practices for each crop.

Throughout the results we may reference other management practices. One practice, tillage, is the primary mechanical method for weed control, and thus a relevant consideration for understanding changes in herbicide usage. Reducing tillage is also an important strategy for soil conservation, soil health and regenerative agriculture and, in many cases, farmers have been able to reduce or eliminate tillage as new herbicide-tolerant crop varieties have enabled chemical control of weeds without damage to the crop. We also know from the 2017 Census of Agriculture that no-till increased 8% from 2012 to 2017, and reduced till increased 28%, across all crop lands in the country [105].

Here we discuss the findings for each of the nine crops. We do not attempt to discuss all pest management challenges for each crop, rather we focus on one or two issues of concern and work across crops to provide an idea of the diversity of pest management challenges and mitigation strategies adopted by farmers. There are a wide variety of pest, weed and disease challenges in agriculture that vary by crop but also based on weather conditions, land use history and other environmental factors. This report is intended as an entry point to inform further in-depth discussions within strategic sustainable agriculture partnerships including local experts about specific pest management challenges and appropriate IPM strategies for growers.

4. Results

Results from the analysis of publicly available data at the national level are provided by crop in four graphics:

a) A background chart showing change over time in crop yield and planted area;

b) The volume of chemical use over time by pesticide category;

c) IPM practice adoption, categorized by practices for Prevention, Avoidance, Monitoring and Suppression;

d) IPM practice highlights and recommendations for increased adoption based on expert input and current adoption rates.

We consulted with farmer representatives for each crop, in addition to relevant literature, to gain insight into the drivers of the observed trends (or lack of trends) in the publicly available data.

4.1 BARLEY

Barley is grown in northern regions of the country, and the data included represent California, Washington, Idaho, Montana, North Dakota, Minnesota and Wisconsin. Overall acreage of land in barley production has declined significantly over the past two decades, while yields have increased (Figure 1a).

Chemical use data are available for just two years, 2003 and 2011, while IPM practice data for barley production are available only for the year 2011, limiting our understanding of pesticides and management practices (Tables 1, 2). In particular, there was high rainfall in 2011 in barley growing regions, which can increase disease pressure and impact pest management decisions, and thus these data may not reflect the most common practices. For the latest year where USDA data are available, 2011, 35% of barley was grown in no-tillage systems. Based on available information, this was a three-fold increase from 2002 in the proportion in no-till systems.

One pest management challenge for barley is the yellow dwarf virus which is spread by several species of the aphid insect pest [106]. IPM strategies to combat the virus include adjusting planting dates to limit exposure to aphids carrying the virus during early crop growth stages, controlling volunteer wheat, barley, oats and wild grasses which may harbor the virus, and confirming presence of the virus by having samples tested at a qualified lab. A small grain crop, barley is also susceptible to the Fusarium head blight (FHB) fungus (see Section 4.9), for which management of crop residues and planning of rotations so that barley does not follow barley, wheat or corn, are important IPM practices to

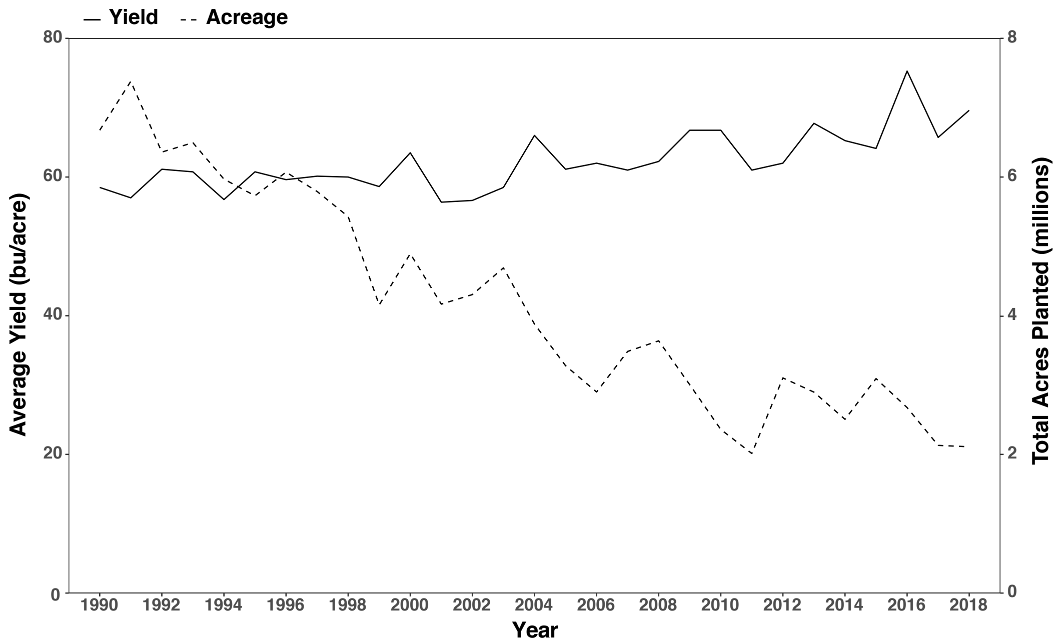

Figure 1a, Barley: Trends for average yield (solid line) and total planted area (dotted line) for barley for 1990−2018. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

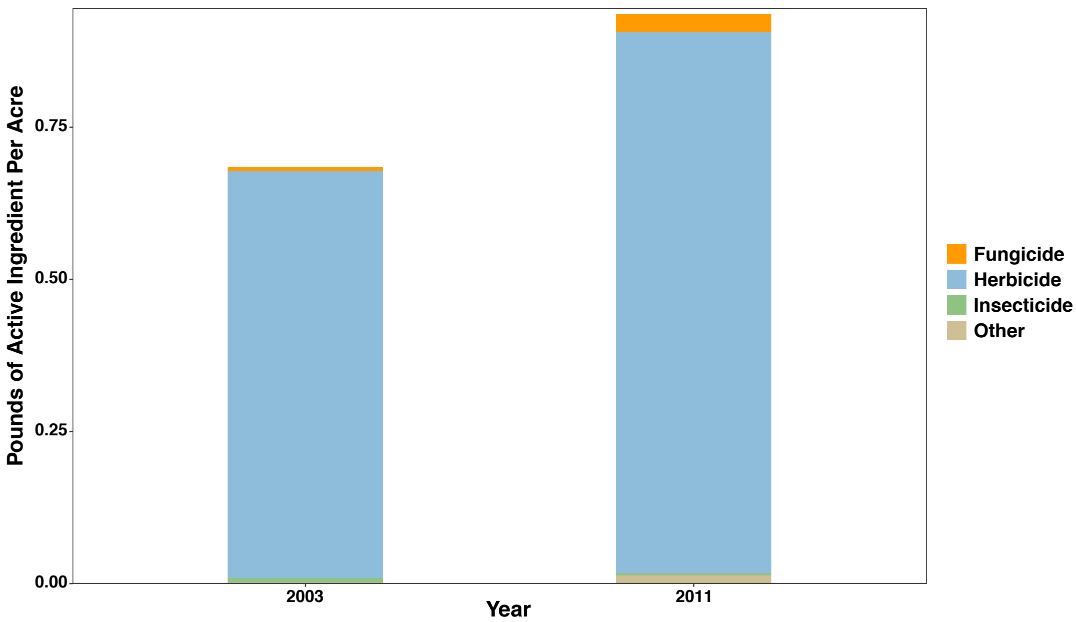

Figure 1b, Barley: Chemical use quantities of herbicides, insecticides, fungicides, and other crop protectants for barley adjusted for planted area. Seed−applied pesticides are not captured by USDA surveys and thus not included in the chemical use quantities. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

consider (Figure 1d). Notably, the last year of available chemical use data for barley is prior to the expansion of corn into northern agricultural regions where barley is grown, which accelerated in 2012 and has been associated with greater instances of FHB disease pressure in wheat. Future surveys and data releases will help to understand how barley growers are responding to this and other pest management challenges.

A unique opportunity for advancing sustainability of barley production is that 75% of the U.S. crop goes into one product — malt for beer production — for a relatively small number of companies. Thus, there is a relatively direct relationship between barley growers and their customers, and sustainability programs instituted by the malt purchasers can significantly impact producer practices. This presents an opportunity for direct supply chain engagement in working with farmers to advance sustainability goals, including advancing responsible pest management practices.

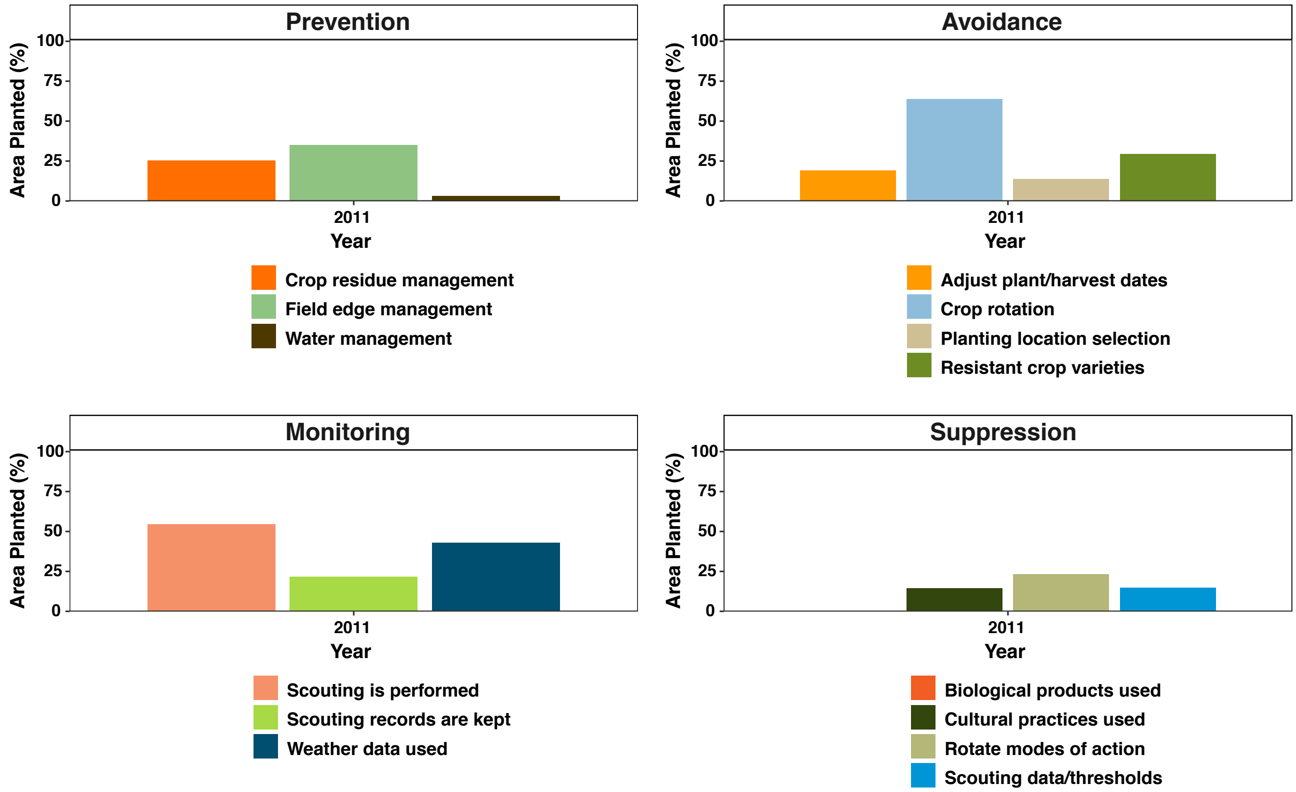

Figure 1c, Barley: Integrated Pest Management practice adoption for barley in percent of area planted and separated by strategy under the Prevention, Avoidance, Monitoring, and Suppression (PAMS) framework. Not all available IPM strategies were included. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

High Adoption (>40%)	Priorities for Adoption
▪ Crop rotation (Avoidance)	▪ Crop residue management (Prevention)
▪ Scouting is performed (Monitoring)	▪ Plant resistant crop varieties (Avoidance)
▪ Weather data used (Monitoring)	▪ Adjust plant/harvest dates (Avoidance)

Figure 1d: IPM practices with relatively high adoption, and key opportunities identified for improvement in barley.

4.2 CORN

With the notable exception of insecticidal and fungicidal seed treatments, a relatively complete set of chemical use data is available for corn, spanning the years from 1991 through 2016, while three years of IPM practice data are available. Data presented here represent corn grown for both grain and for silage, as USDA does not distinguish between the two purposes and harvest methods in the survey. Over this time period, both acres planted to corn and corn yields have increased substantially (Figure 2a). This time period includes constant improvements in hybrids through classical breeding and spans the introduction of GE corn varieties with plant-incorporated insecticide (Bt) and with herbicide tolerance traits; these traits have been widely adopted, driving changes in pest management practices for corn.

The chemical trends data from USDA show declines in insecticide applications by weight, which correspond to the increased adoption of plant-incorporated insecticide variety adoptions as well as of seeds treated with insecticide which are not included in the data (Figure 2b). There is some research that has shown that adoption of neonicotinoid seed treatments has resulted in more extensive area of corn and soybean applying insecticide [107] and the amounts of insecticide active ingredients being applied to seed do not appear to be decreasing [108]. Seed treatments are applied at the seed supplier distribution centers, and thus individual farmer decisions on whether to purchase insecticide as a seed treatment is limited by what seed characteristics are made available at the retail sales point.

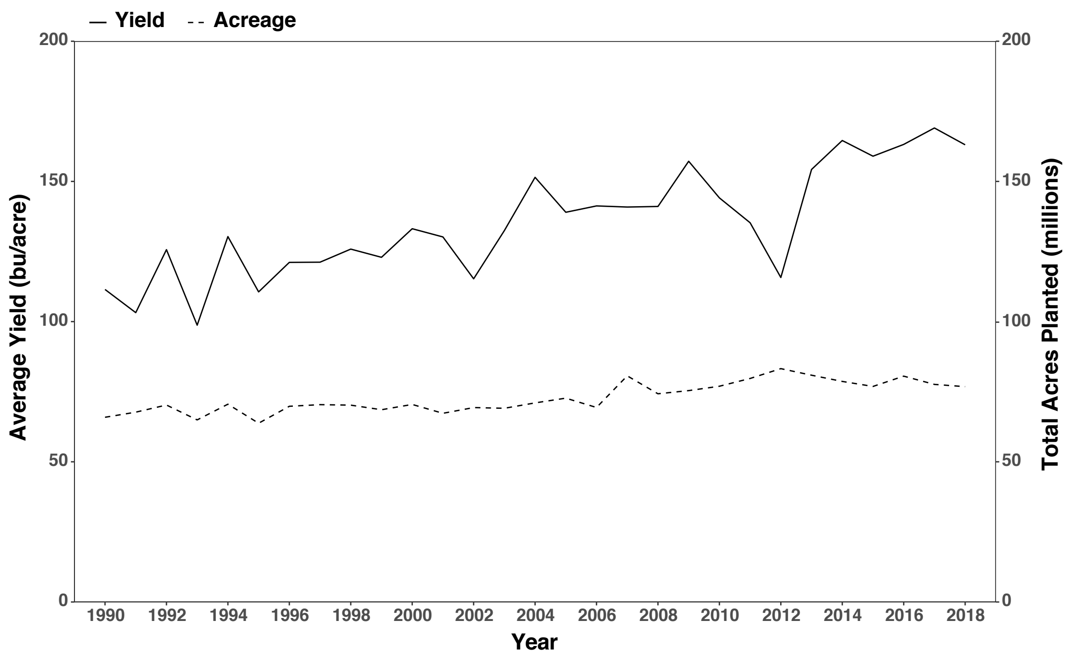

Figure 2a, Corn: Trends for average yield (solid line) and total planted area (dotted line) for corn for 1990−2018. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

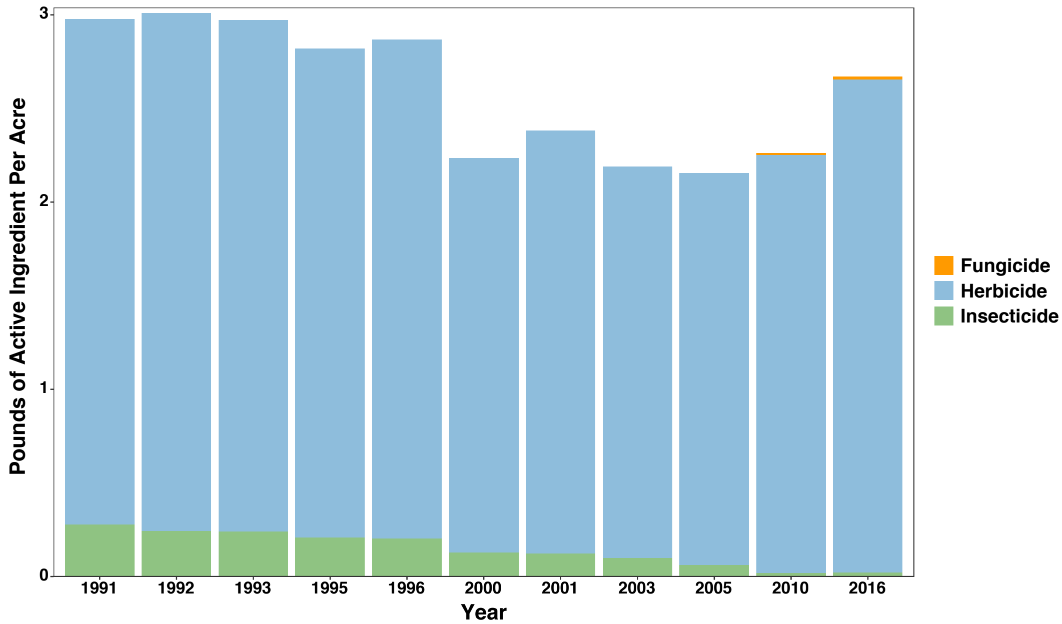

Figure 2b, Corn: Chemical use quantities of herbicides, insecticides, fungicides, and other crop protectants for corn adjusted for planted area. Seed−applied pesticides are not captured by USDA surveys and thus not included in the chemical use quantities. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

Quantities of herbicide have fluctuated somewhat, largely as a consequence of the change in type of herbicide applied as different products have different effective application rates. Herbicide treatments have also increased as they are used to enable adoption of soil conservation practices, including conservation and no-tillage systems, and cover crops. Most recently, increasing herbicide applications have been used in the treatment of herbicide-resistant weeds, as multiple chemicals and larger volumes may be applied to an affected field.

The IPM management practices from 2010 through 2016 show no discernable trend or change over time (Figure 2c). Several practices are widely adopted in corn production, including crop rotation (primarily with soybean), the use of resistant crop varieties, and scouting for pest damage. Use of scouting and thresholds to inform pesticide applications has relatively low adoption, as the use of Bt corn varieties reduced the risk from soil pests such as rootworm. As resistance to Bt has emerged in corn rootworm populations, scouting has increased. Crop rotation has the highest adoption rate, practiced on 84% of corn acres planted in 2018 due to myriad benefits. For example, the corn rootworm deposits eggs in the soil of corn fields that hatch the following spring. By ensuring a rotation where the corn is followed by a different crop, the rootworm larvae will not survive, breaking the pest life cycle for that field. Challenges to rotating crops every year, however, include factors outside the control of the farmers, such as weather and market conditions in the spring that influence planting decisions. In addition, some rootworm species and populations in parts of the Midwest have adapted to crop rotation by depositing eggs in non-corn crop fields (including soybeans) which then may be planted to corn the following year, and by “extended diapause” where egg hatch is delayed one or more years. Growers may manage these variants where present by scouting for corn rootworm in soybean fields [109], but primarily opt for Bt hybrids for corn rootworm management to minimize risk and negate the need for scouting.

Emerging pest management challenges for corn include herbicide-resistant weeds and corn rootworm and earworm resistance to the plant-incorporated pesticide in Bt corn varieties. At least sixty species of weeds common in corn fields are resistant

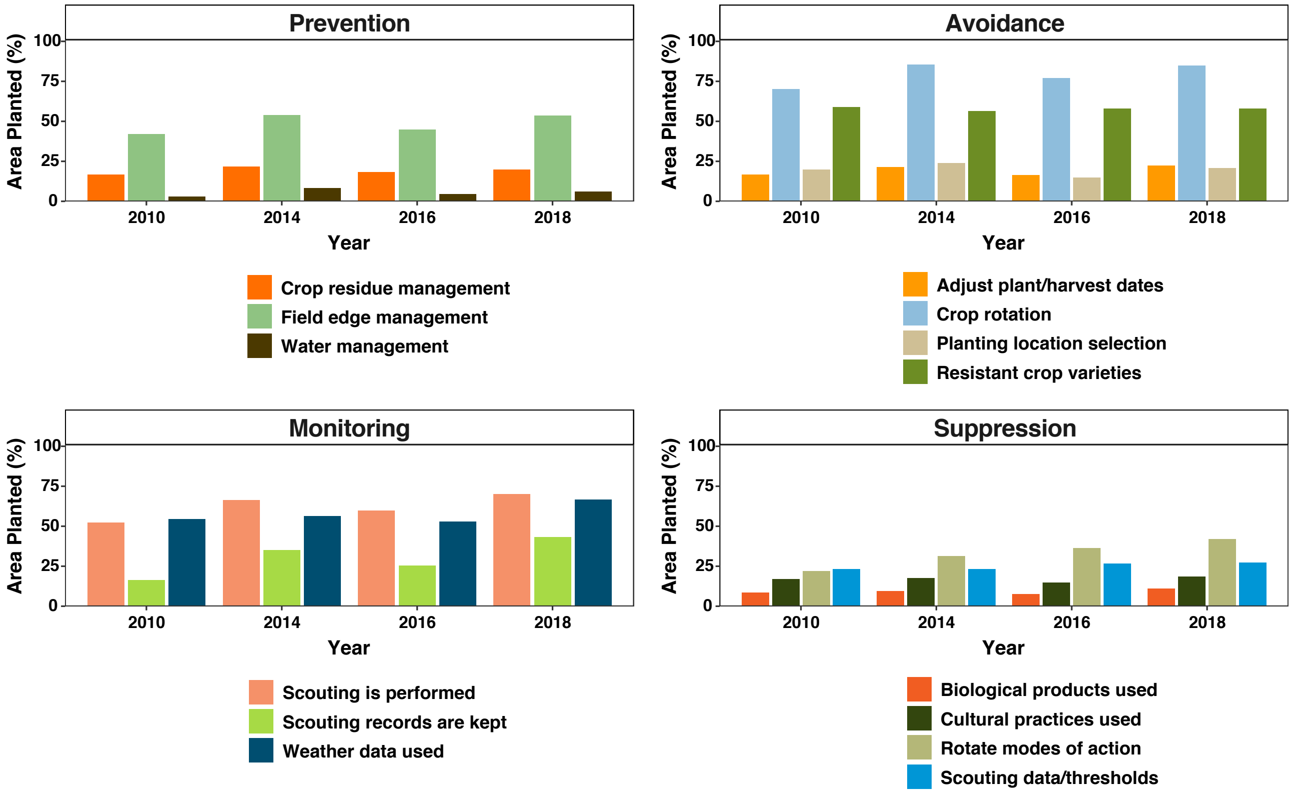

Figure 2c, Corn: Integrated Pest Management practice adoption for corn in percent of area planted and separated by strategy under the Prevention, Avoidance, Monitoring, and Suppression (PAMS) framework. Not all available IPM strategies were included. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

to at least one herbicide mode of action, complicating weed management. Rotating corn with soybeans that have the same GE herbicide tolerance traits (i.e. glyphosate) can compound the herbicide resistant weed problem as it encourages use of the same chemical modes of action in successive years. Adding additional crops, including cover crops, and/or selecting varieties that allow for more rotation of different herbicide modes of action are strategies that can help manage resistant weeds. Introduction of novel herbicide tolerance traits into the crop has also been deployed as a strategy to manage resistant weeds.

Almost all corn seed available to farmers comes pre-treated with insecticidal seed treatments that were initially thought to reduce the exposure of non-target insects to the insecticide, while at the same time increasing the exposure of pest or target insects. They have been considered easier to use and more effective than post-planting pesticide applications. Insecticide seed treatments may control several soil-dwelling insects that are challenging to monitor. However, data demonstrating the benefits and cost effectiveness of this approach are scarce [110], as the target pests are sporadic and uncommonly encountered [111].

Widespread use of seed treatments has led to the need for improvements in seed coating technology and planting equipment such as better sealing, gasketing, and filtering to minimize insecticide-contaminated dust drift created by pneumatic planting equipment, as this can increase impacts on populations of non-target insects including beneficial species [112,113]. In some areas, populations of non-insect pests like slugs and mites can be exacerbated by the effects of the neonicotinoid seed treatments [114,115]. There is an opportunity to reduce both seed costs and negative impacts by aligning the use rates more closely with the likelihood of target pest infestations. To enable greater adoption of IPM principles, farmers need to have the choice to select seeds with only the desired traits, including without seed treatments and cost-effective sampling tactics for pests that are currently very difficult to monitor and predict, such as wireworms and seed corn maggot, that are effectively controlled by insecticide seed treatment.

High Adoption (>40%)	Priorities for Adoption
Crop rotation (Avoidance)	Rotate modes of action (Suppression)
Scouting is performed (Monitoring)	Planting location selection (Avoidance)
Resistant crop varieties (Avoidance)	Scouting data/thresholds (Suppression)
Weather data used (Monitoring)	
Field edge management (Prevention)	

Figure 2d: IPM practices with relatively high adoption, and key opportunities identified for improvement in corn.

4.3 COTTON

Cotton is produced largely in the southern United States, and the data analyzed here are for Texas, Arkansas, Missouri, Alabama, Georgia, Mississippi, Tennessee, and North Carolina. Since 1990, acreage in cotton has fluctuated, while yields have steadily increased as new higher yielding and disease resistant varieties and genetically engineered seed with plant-incorporated pesticide (Bt) have been introduced and the boll weevil pest has been eradicated (Figure 3a). Data on chemical use and IPM practices are only available for three years of the time period — 2007, 2015, and 2017 — providing us with a view over the past decade. As with corn, data for cotton do not include seed-applied insecticides, which are in near universal use.

Cotton is a crop that favors warm weather and is grown in southern regions of the country; as a consequence, it is subject to high insect pest pressure, with boll weevil, tobacco budworm and pink bollworm as some of the primary threats. Bt cotton was introduced in 1996 and has been highly effective at reducing damage from these pests, reducing the need for insecticide applications and increasing yields. Bt cotton has been adopted on about 85% of cotton acreage in the U.S. In recent years reports of Bt resistant bollworm have emerged, which has accounted for substantial crop yield losses [116] and farmers have had to diversify pest management practices in response [117]. Herbicide tolerant GE cotton has also been widely adopted on over 80% of acres planted; one of the biggest pest management challenges for cotton growers has become managing herbicide resistant weeds (see sections 4.2 and 4.8). Greater adoption of cultural practices to manage weed seed banks,

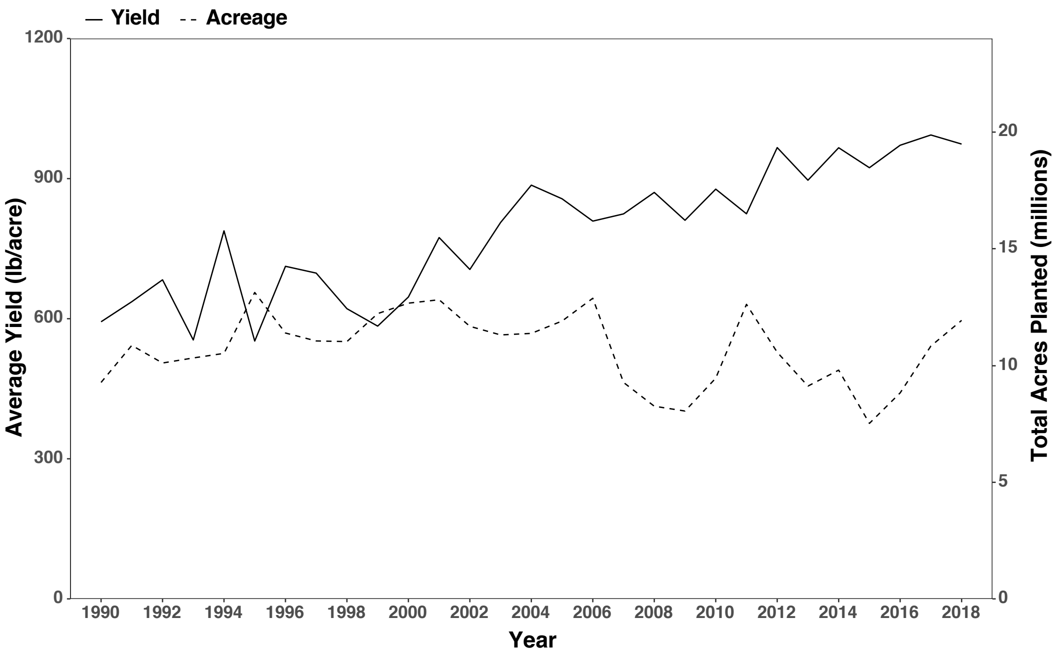

Figure 3a, Cotton: Trends for average yield (solid line) and total planted area (dotted line) for cotton for 1990−2018. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

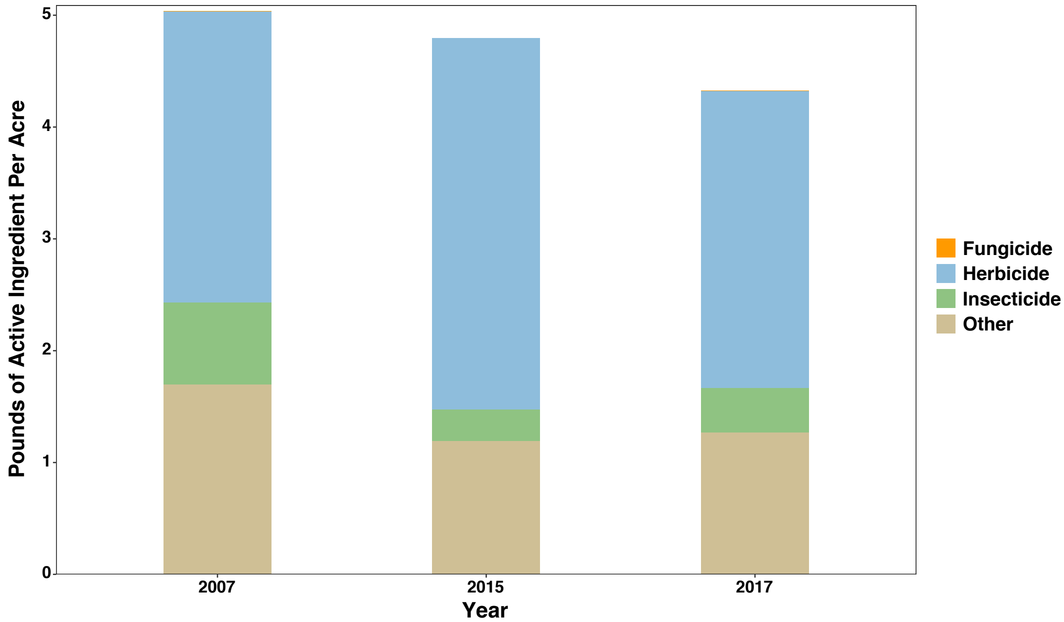

Figure 3b, Cotton: Chemical use quantities of herbicides, insecticides, fungicides, and other crop protectants for cotton adjusted for planted area. Seed−applied pesticides are not captured by USDA surveys and thus not included in the chemical use quantities. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

such as cover crops and mechanical seed destruction could help to manage weed pressure in cotton.

The chemical use data overall show a reduction in amounts over the past decade (Figure 3b), but the data do not account for seed-applied insecticides which are widely used [107]. Cotton production also involves the use of plant growth regulating chemicals, to manage the size of the plants, as well as harvest aids to facilitate equipment use during harvest. These make up the "other" category in Figure 3b.

IPM practice data for cotton are available for three years and illustrate an increase in crop rotation — from 37% adoption in 2007 to over 60% in 2017. Specific rotations can be used to manage for specific pests; for example, rotating cotton with peanuts has been shown to reduce the incidence of root-knot nematodes in cotton years [118]. The IPM practice data also indicate some increase in the rotation of modes of action of pesticides. Crop varieties bred to resist certain pests, including nematodes, and diseases include cotton leaf blight also have relatively high adoption. Overall, the greatest adoption is of monitoring practices, such as scouting to identify whether a pest is present and whether the damage being caused warrants chemical treatment to protect against yield damage or loss (Figure 3c).

For the current challenges, increasing compliance with non-Bt refuges — the practice of incorporating areas without the Bt trait in a field, farm and region — is an important strategy for reducing the rate of Bt resistance development and preserving the effectiveness of these plant incorporated insecticides. There is also a continuing need for varieties bred for insect resistance. Widespread prophylactic use of neonicotinoid seed treatments in row crops, particularly in areas where seed-treated cotton and soybean are both grown, has also led to development of resistance in the tobacco thrips, an insect pest that economically damages cotton [63]. Thus, better cross-crop resistance management and IPM plans need to be adopted in situations where common crop rotations include tolerance traits or treatments using the same pesticide modes of action.

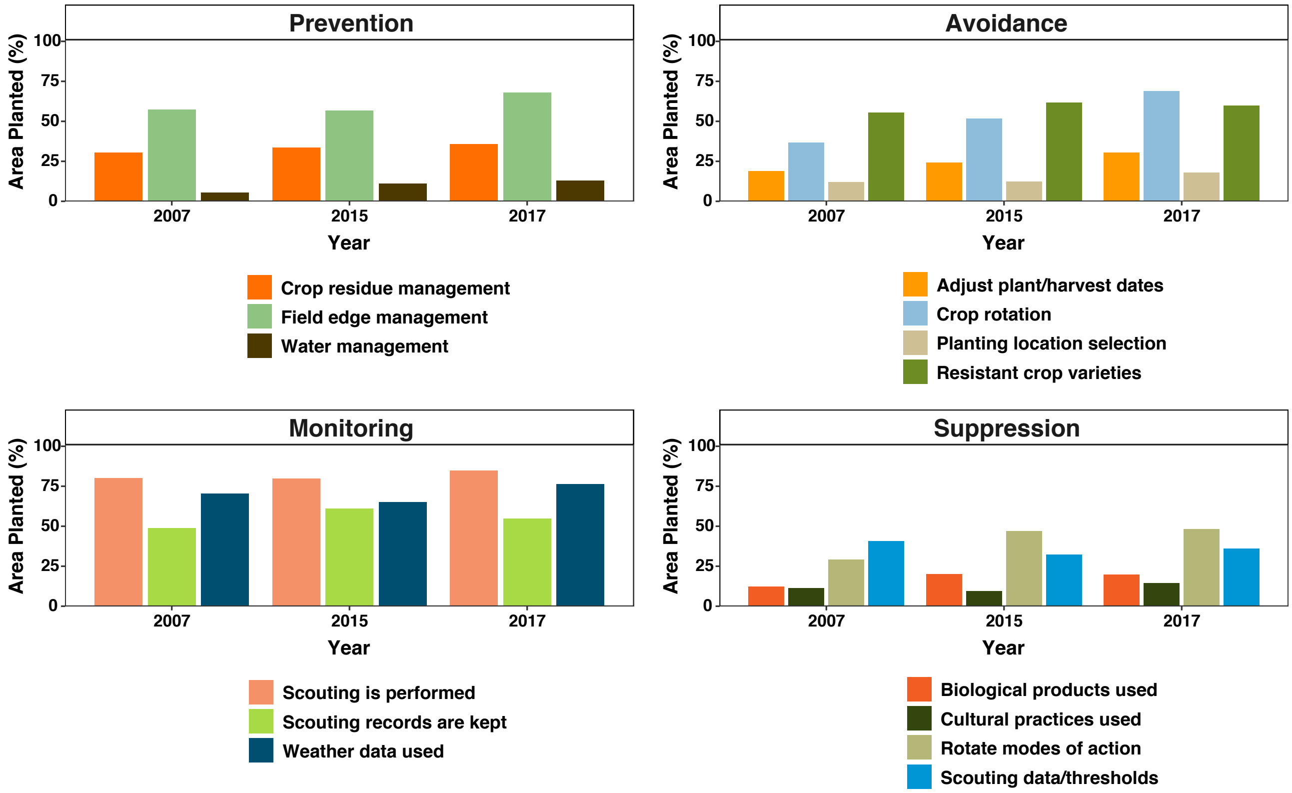

Figure 3c, Cotton: Integrated Pest Management practice adoption for cotton in percent of area planted and separated by strategy under the Prevention, Avoidance, Monitoring, and Suppression (PAMS) framework. Not all available IPM strategies were included. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

High Adoption (>40%)	Priorities for Adoption
▪ Scouting is performed (Monitoring)	▪ Water management (Prevention)
▪ Weather data used (Monitoring)	▪ Cultural practices used (Suppression)
▪ Field edge management (Prevention)	▪ Scouting data/thresholds (Suppression)
▪ Resistant crop varieties (Avoidance)	
▪ Crop rotation (Avoidance)	
▪ Rotate modes of action (Suppression)	

Figure 3d: IPM practices with relatively high adoption, and key opportunities identified for improvement in cotton.

4.4 PEANUTS

Peanuts are grown across the south, and the data included here are from Texas, Alabama, Georgia and North Carolina. Overall acres planted to peanuts have declined since around 2000, while yields have substantially increased (Figure 4a). This has coincided with a shift in the primary peanut growing regions towards the southeastern states [119].

Peanuts are susceptible to damage from several pests found in soils, including nematodes and the fungus Cylindrocladium black rot (CBR). CBR can cause high yield losses, particularly in cool, wet years and can be managed by crop rotations incorporating non-host plants, using a resistant crop variety, and planting on raised beds to keep the soil dry and warm early in the season. Chemical treatment for CBR involves the use of soil fumigants, which are included in the "other" category in Figure 4b. The reduction in this category for the last year of data available most likely represents a combination of factors, including weather conditions in that year. Another disease impacting peanuts is tomato spotted wilt virus (TSWV), which emerged in the early 2000s.

CBR can have a greater impact when combined with insect pest damage, and TSWV is transmitted by an insect pest (thrips). Thus, management for these challenges must be a coordinated strategy accounting for the biology and lifecycle of primary pest causing direct damage, as well as the related contributing factors. Adoption of resistant varieties and other cultural management practices that reduce the susceptibility of the crop to these diseases can help reduce both fungicide and insecticide applications. Research has found that adoption of conservation tillage practices can reduce disease pressure

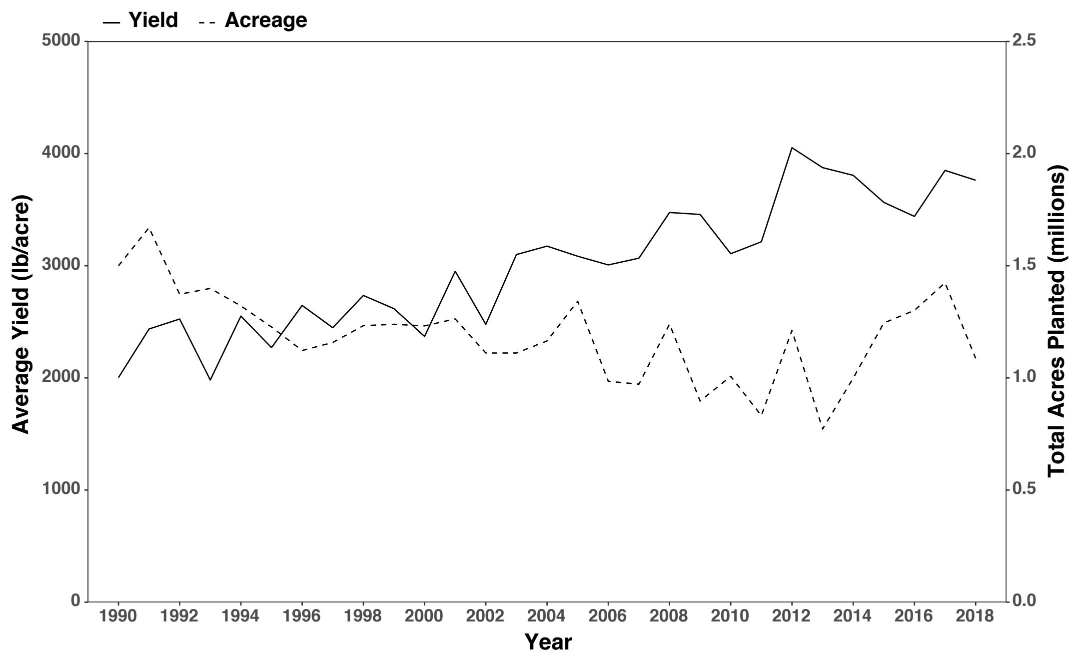

Figure 4a, Peanuts: Trends for average yield (solid line) and total planted area (dotted line) for peanuts for 1990−2018. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

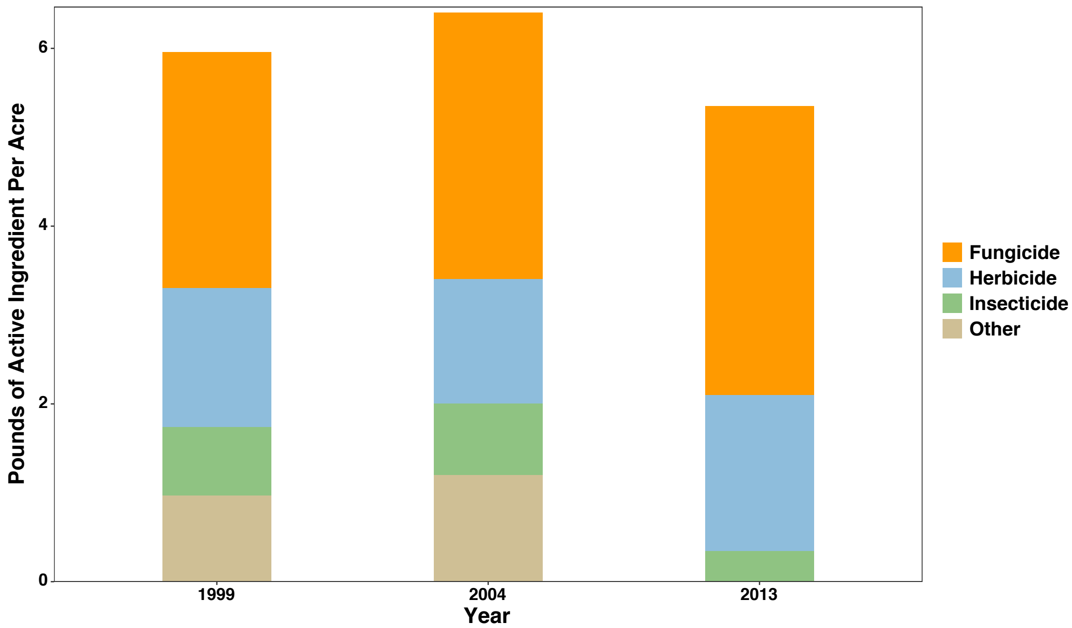

Figure 4b, Peanuts: Chemical use quantities of herbicides, insecticides, fungicides, and other crop protectants for peanuts adjusted for planted area. Seed−applied pesticides are not captured by USDA surveys and thus not included in the chemical use quantities. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

---

and damage to peanut yield while also conserving water [120].

The IPM practice data for peanuts, while only available for two years, show a high adoption rate for crop rotations – over 90% in 2018 (Figure 4c). One of the most effective strategies for reducing multiple diseases in peanuts is a three-year or longer rotation with non-legume crops [121]. Reduced tillage can also help in the mitigation of multiple insect pests, and USDA data indicate increasing adoption of reduced till in peanut production. Scouting for damage and diagnosing the specific pest prior to treatment is also critical. Land-Grant Universities in peanut growing states are active in publishing alerts for growers on risk factors for pest damage, such as high populations of contributing insects or weather conditions favorable for disease, as well as guides on identification of the specific pest. Such resources can assist growers to take pro-active steps to protect their crops.

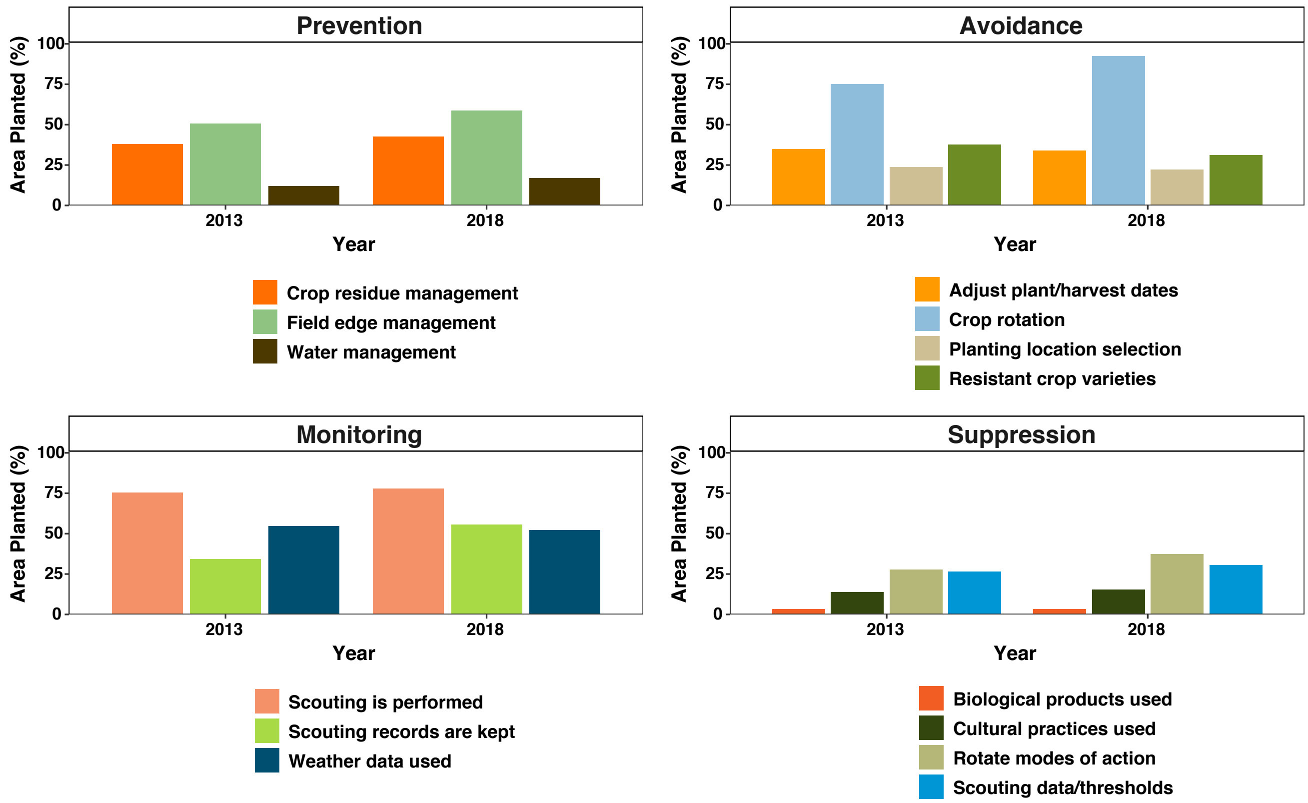

Figure 4c, Peanuts: Integrated Pest Management practice adoption for peanuts in percent of area planted and separated by strategy under the Prevention, Avoidance, Monitoring, and Suppression (PAMS) framework. Not all available IPM strategies were included. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

High Adoption (>40%)	Priorities for Adoption
▪ Crop rotation (Avoidance)	▪ Rotate modes of action (Suppression)
▪ Scouting is performed (Monitoring)	▪ Resistant crop varieties (Avoidance)
▪ Field edge management (Prevention)	▪ Scouting data/thresholds (Suppression)
▪ Weather data used (Monitoring)	
▪ Scouting records are kept (Monitoring)	
▪ Crop residue management (Prevention)	

Figure 4d: IPM practices with relatively high adoption, and key opportunities identified for improvement in peanuts.

4.5 POTATOES

Potatoes are a root vegetable crop typically grown in a multi-year rotation with other commodities considered in this report. Nearly three-quarters of the potatoes grown in the U.S. are for processing, with the majority of the remainder used for fresh, or table stock [122]. Since 1990 yield has steadily increased while area planted to potatoes has declined (Figure 5a).

Potatoes, like peanuts, are a root crop and therefore have a higher use of soil fumigants to protect against soil borne disease and pesticides to control nematodes (the "other" category in Fig 5b), which is most common in western areas (Figure 5b). The supply of one of these products, a nematicide, was disrupted in 2015 due to an accident at the chemical manufacturing facility that stopped production. This supply interruption contributed to the decline in volume applied that is observed in the data in 2016. In addition, the EPA registration renewal for products has led to some reductions in use with new rules regarding rates and timing of chemical applications.

The IPM practice data indicate near universal use of crop rotations in potato, with high adoption of pest monitoring activity as well (Figure 5c). These practices are essential for managing insect and disease pests in potato by using rotations to break the life cycle and scouting to identify problems early. The genetics of potatoes are complex, which leads to slower development and breeding of new crop varieties that are disease resistant. Another complicating factor for IPM practice adoption is that crop residues on a field can impede harvest and lead to foreign material intermingled with the harvested potatoes,

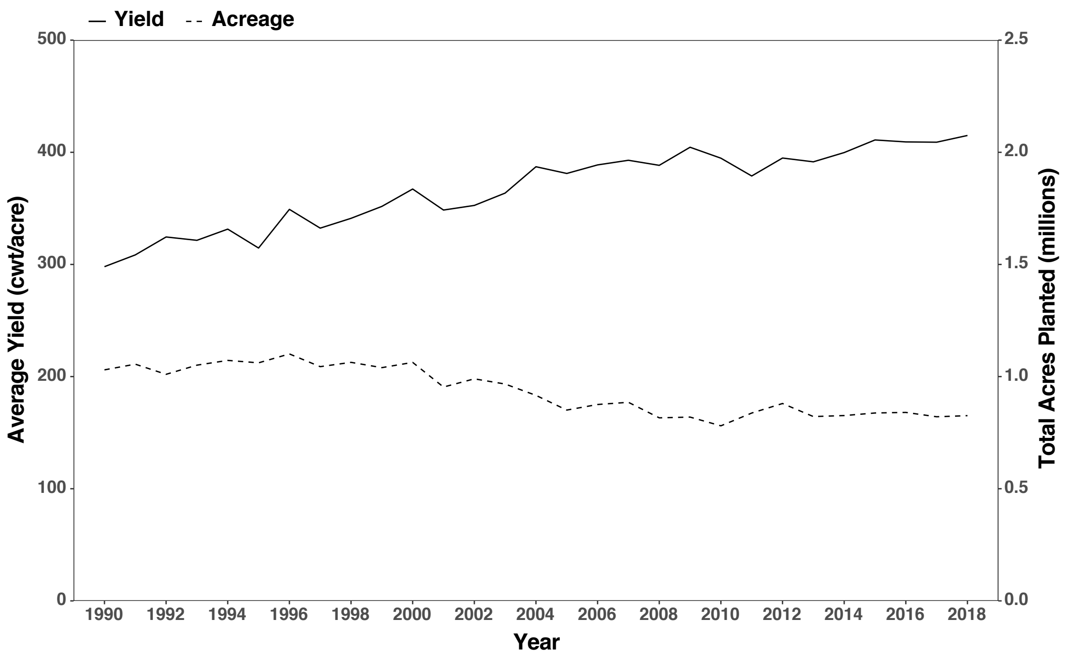

Figure 5a, Potatoes: Trends for average yield (solid line) and total planted area (dotted line) for potatoes for 1990−2018. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

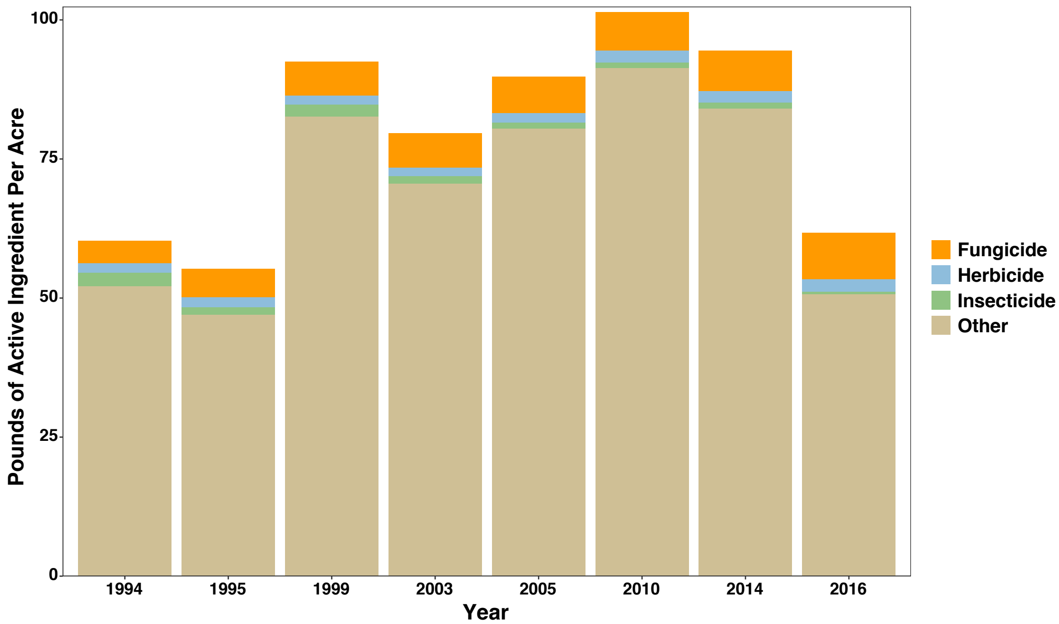

Figure 5b, Potatoes: Chemical use quantities of herbicides, insecticides, fungicides, and other crop protectants for potatoes adjusted for planted area. Seed−applied pesticides are not captured by USDA surveys and thus not included in the chemical use quantities. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

which leads to complications at the delivery point. For this reason, potatoes typically follow a low residue crop in the rotation.

The vast majority of U.S. potatoes are grown from certified seed, which is inspected and certified to be free of disease by third-party inspectors. Potato growers also benefit from well-developed Cooperative Extension networks in multiple states which provide alerts when conditions are right for pest activity including late blight disease, which can cause extensive crop loss if not controlled. The pathogen can travel long distances on weather fronts and timely notification of newly infected plants in an area, or potential for new infections can facilitate prompt action to scout, treat or eliminate the infection.

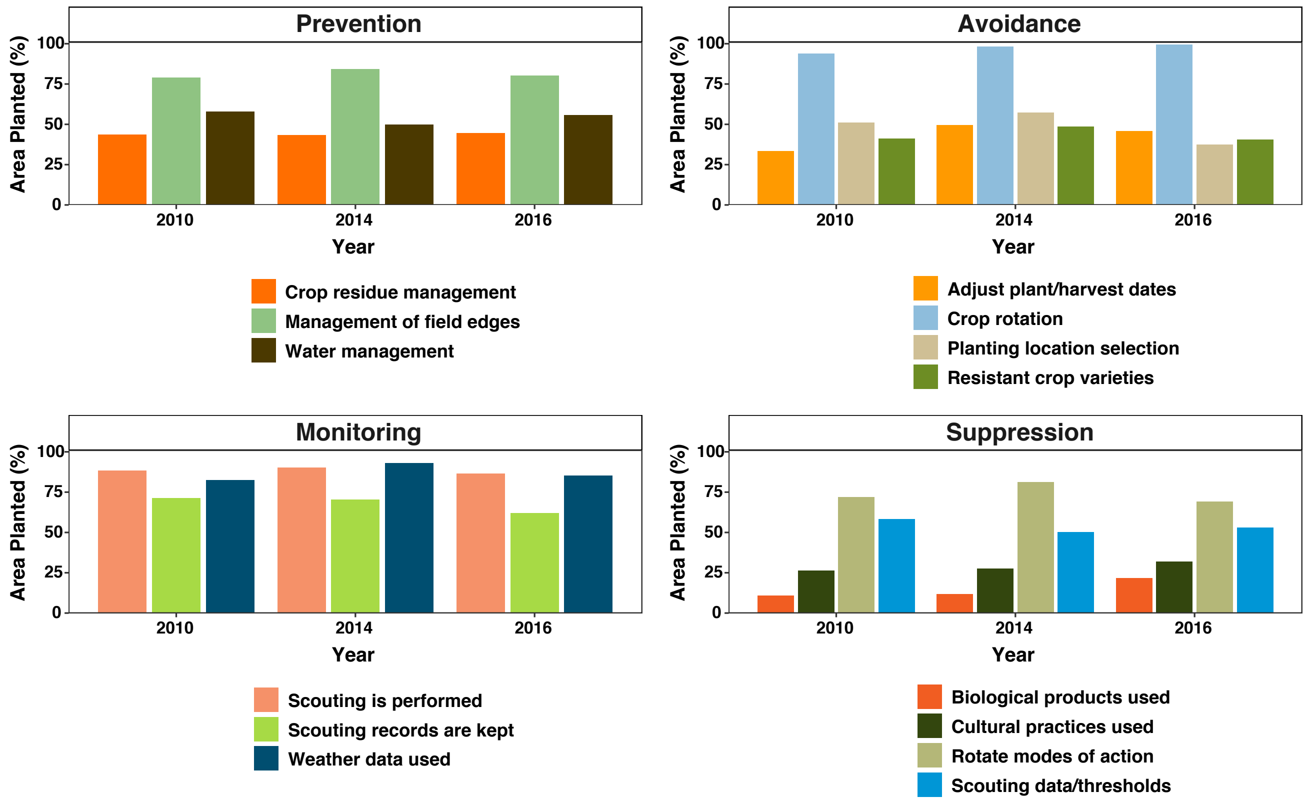

Figure 5c, Potatoes: Integrated Pest Management practice adoption for potatoes in percent of area planted and separated by strategy under the Prevention, Avoidance, Monitoring, and Suppression (PAMS) framework. Not all available IPM strategies were included. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

High Adoption (>60%)	Priorities for Adoption
▪ Crop rotation (Avoidance)	▪ Planting location selection (Avoidance)
▪ Scouting is performed (Monitoring)	▪ Crop residue management (Prevention)
▪ Weather data used (Monitoring)	▪ Adjust plant/harvest dates (Avoidance)
▪ Field edge management (Prevention)	▪ Resistant crop varieties (Avoidance)
▪ Rotate modes of action (Suppression)	
▪ Scouting records are kept (Monitoring)	

Figure 5d: IPM practices with relatively high adoption, and key opportunities identified for improvement in potato.

4.6 RICE

Rice production in the United States occurs in the mid-South and in California; data presented here are from California, Texas, Arkansas, Louisiana and Mississippi. Acreage has held relatively steady with a small decline since 1990, while yields have steadily increased (Figure 6a). The two growing regions have very distinct differences in weather, with humid and wet summers in the mid-South and dry summers in California influencing not just irrigation requirements but all aspects of rice production practices. While three years of chemical use data are available, IPM practice adoption data are available only for 2013.

Rice is grown on flooded fields, which helps to suppress weeds. However, a closely related plant, "weedy rice" presents a weed challenge in that it closely resembles rice in the early stages of growth; it can be difficult to identify in a rice field and herbicides which target weedy rice can also damage the grain crop. While no genetically engineered rice variety has been commercialized, herbicide tolerant varieties have been developed using traditional breeding techniques and is used in the mid-South growing region in the U.S. This has been an important development to help in management of "weedy rice" by enabling herbicide treatments that target the weed without damaging the rice (Figure 6b).

One critical pest, the rice water weevil, can to some extent be managed through cultural practices including water and field edge management practices. In low rainfall areas, periodic drainage to dry the field can help reduce the pest. While furrow irrigation can help to control the rice water weevil, it is not widely adopted. These water management practices can

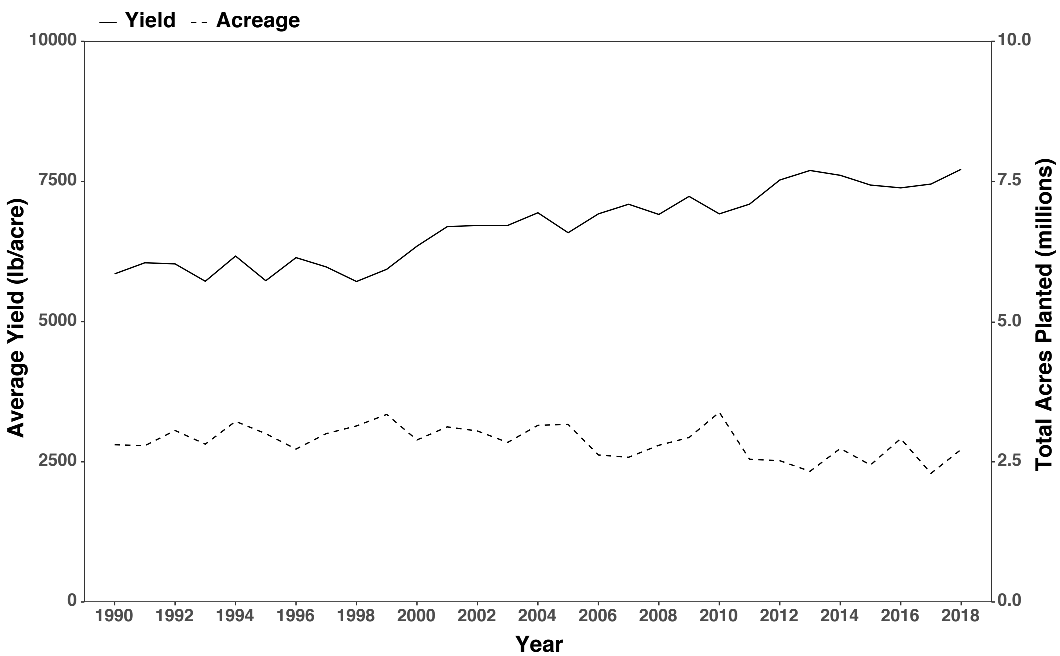

Figure 6a, Rice: Trends for average yield (solid line) and total planted area (dotted line) for rice for 1990–2018. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

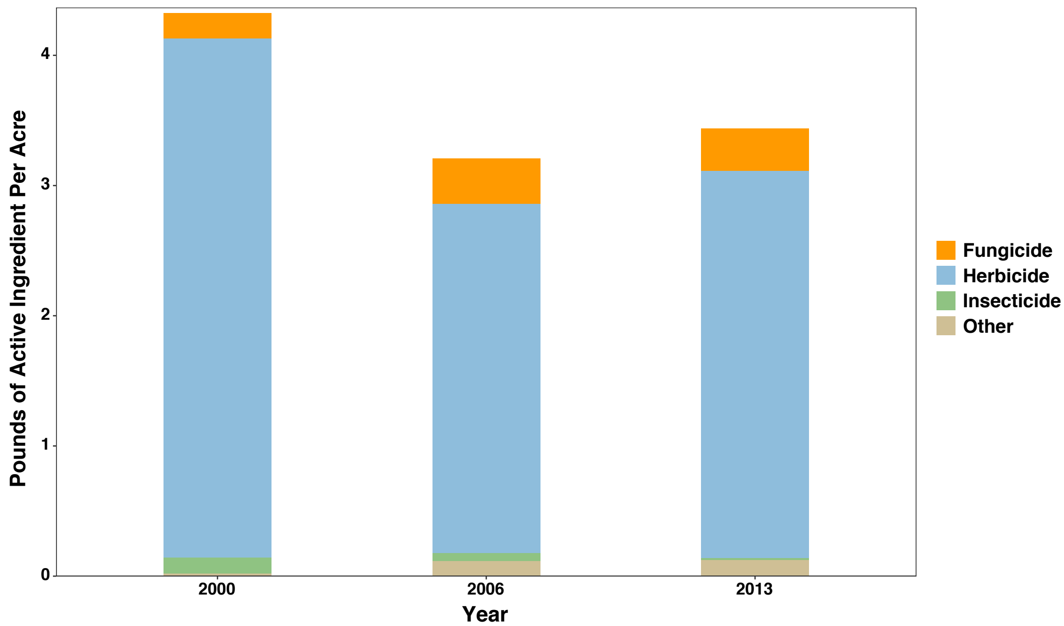

Figure 6b, Rice: Chemical use quantities of herbicides, insecticides, fungicides, and other crop protectants for rice adjusted for planted area. Seed−applied pesticides are not captured by USDA surveys and thus not included in the chemical use quantities. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

be challenging to adopt and effective only under the right environmental conditions; thus insecticides, including seed treatment, remain the primary mode of control for the rice water weevil. Field edge management is also important for insect control in rice production systems in California, although is less effective in the south.

The IPM practice data for rice are only available for one year, 2013, which limits insights that can be drawn from the information. The data indicate high levels of adoption of field edge management, which is important for management of the rice water weevil in California and to reduce habitat for rice stink bugs (Figure 6c). Another important practice is to plan for early planting dates when possible in order to avoid high nighttime temperatures in late summer. IPM practices that are important include crop rotation, in particular with corn or cotton, as soybean and rice can be affected by some of the same diseases and therefore ensuring the rotation includes a non-host crop for the disease will be most effective. In addition, priority areas for IPM adoption include greater scouting frequency and use of economic thresholds to determine when an intervention is needed. IPM adoption would be assisted by better methods to easily sample for and identify pests, and development of more resistant varieties of rice.

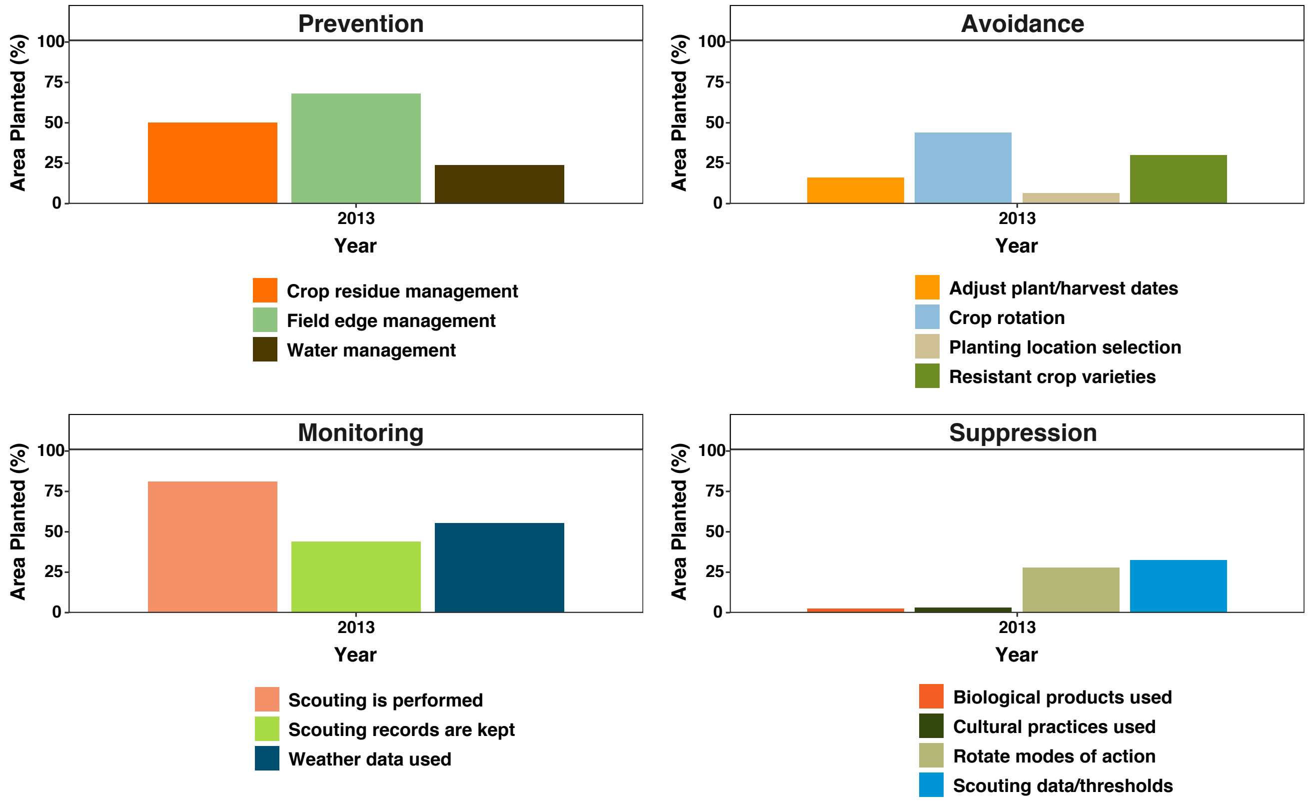

Figure 6c, Rice: Integrated Pest Management practice adoption for rice in percent of area planted and separated by strategy under the Prevention, Avoidance, Monitoring, and Suppression (PAMS) framework. Not all available IPM strategies were included. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

High Adoption (>40%)	Priorities for Adoption
Scouting is performed (Monitoring)	Resistant crop varieties (Avoidance)
Field edge management (Prevention)	Water management (Prevention)
Weather data used (Monitoring)	Scouting data/thresholds (Suppression)
Crop residue management (Prevention)	
Crop rotation (Avoidance)	
Scouting records are kept (Monitoring)	

Figure 6d: IPM practices with relatively high adoption, and key opportunities identified for improvement in rice.

4.7 SORGHUM

Sorghum is a drought-tolerant crop grown in the south-central Plains states. The data presented here are from Texas, Oklahoma, Kansas, Colorado, Nebraska, and South Dakota. Sorghum is frequently grown without irrigation and national average yields over time show fluctuations where low yields correspond to drought years. USDA data for both chemical use and IPM practices were collected during these drought years, and so may not reflect typical circumstances and growing practices as some pests are more problematic in dry years. Overall, yield has increased since 1990 while area planted has declined (Figure 7a).

Data on chemical use in sorghum is limited to two years (Figure 7b), with only one year of IPM practice information (Figure 7c). While there is no genetically engineered sorghum, traditional breeding has produced hybrids with some natural resistance to common pests. The most damaging pest is the sugarcane aphid, which can be managed through practices such as early planting, using varieties bred for resistance, and scouting to prevent economic yield loss. Another damaging insect pest is the sorghum midge, which has a short lifecycle (14–16 days) and thus can quickly worsen over the course of a growing season. Early planting can also help mitigate the midge by ensuring that key plant-development stages occur prior to high levels of midge infestation. The midge and sugarcane aphid are both common on Johnsongrass, a fast-growing perennial weed, so management of field edges to eliminate Johnsongrass is also an effective strategy, as is incorporating sorghum residues into the soil after harvest.

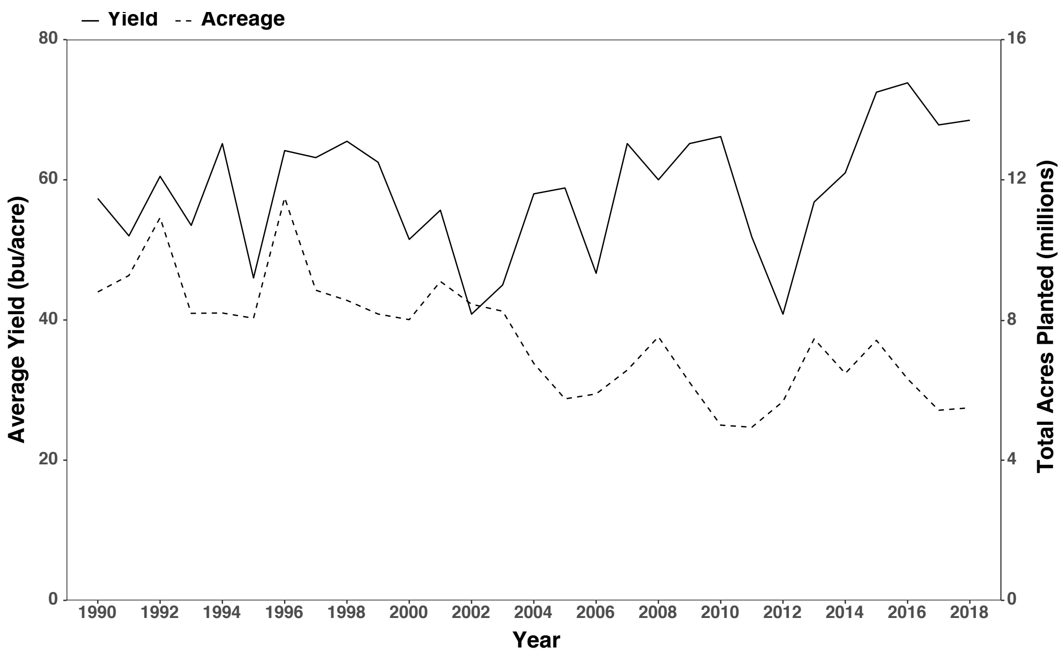

Figure 7a, Sorghum: Trends for average yield (solid line) and total planted area (dotted line) for sorghum for 1990−2018. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

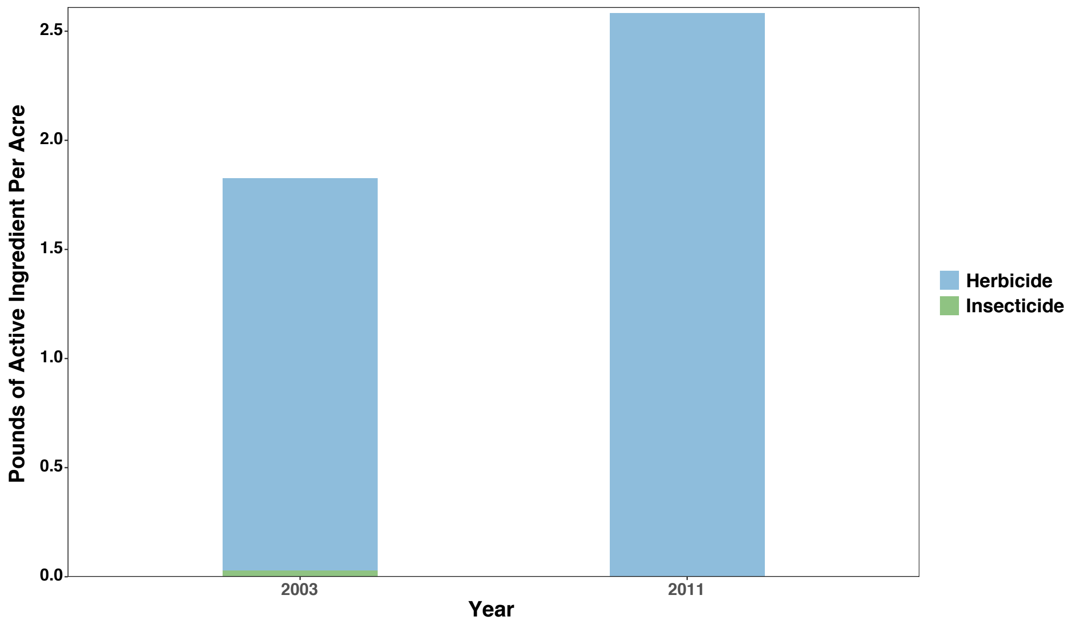

Figure 7b, Sorghum: Chemical use quantities of herbicides, insecticides, fungicides, and other crop protectants for sorghum adjusted for planted area. Seed−applied pesticides are not captured by USDA surveys and thus not included in the chemical use quantities. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

In rainfed sorghum, weeds can lead to yield losses of up to 24% due to competition for limited water in the field [123]; however, herbicide tolerant hybrid sorghum has only recently been developed through traditional breeding and has not yet been widely adopted. Adoption must be carefully managed to prevent the tolerance trait spreading to Johnsongrass, which can cross-breed with sorghum. While IPM practice information is available for only one year, it does show high adoption rates for crop rotation and scouting. Sorghum growers work extensively with University extension specialists to monitor for pest damage across the growing regions.

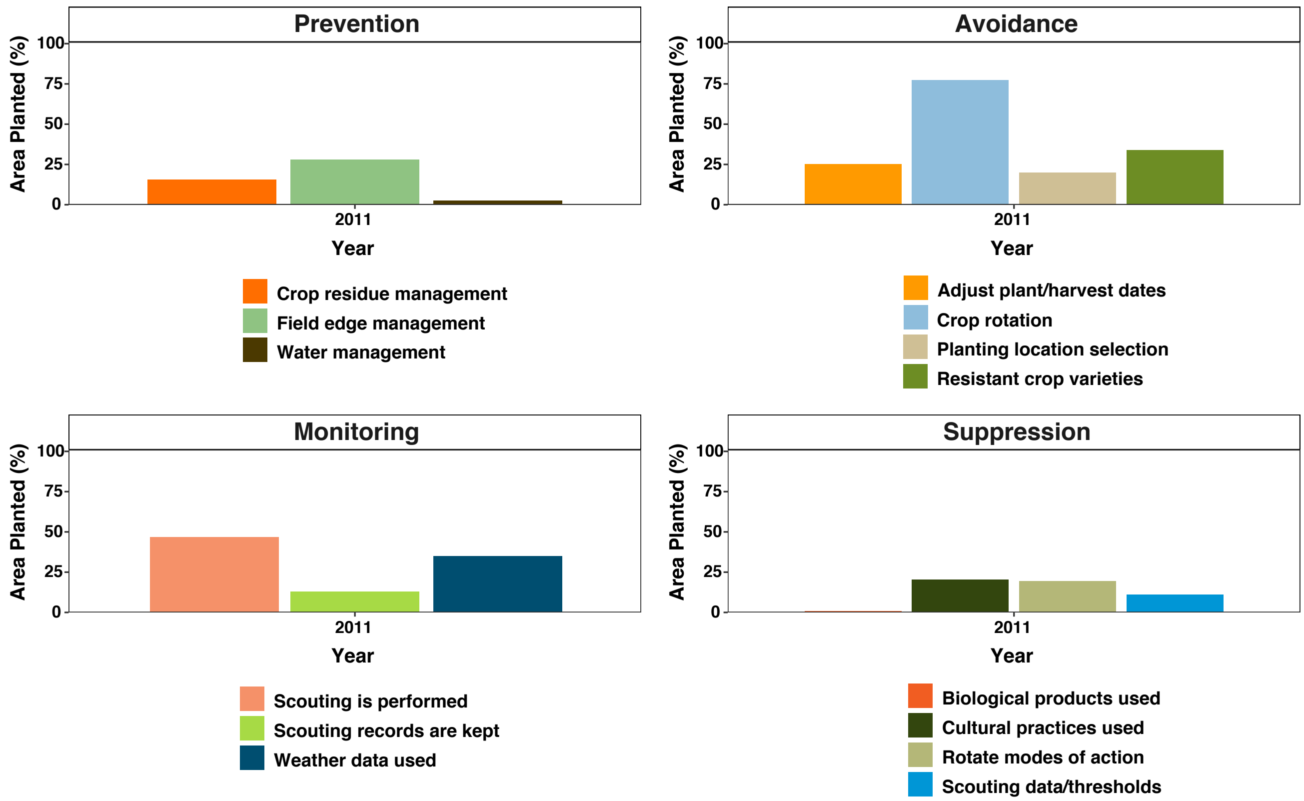

Figure 7c, Sorghum: Integrated Pest Management practice adoption for sorghum in percent of area planted and separated by strategy under the Prevention, Avoidance, Monitoring, and Suppression (PAMS) framework. Not all available IPM strategies were included. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

High Adoption (>40%)	Priorities for Adoption
▪ Crop rotation (Avoidance)	▪ Rotate modes of action (Suppression)
▪ Scouting is performed (Monitoring)	▪ Weather data used (Monitoring)
	▪ Field edge management (Prevention)

Figure 7d: IPM practices with relatively high adoption, and key opportunities identified for improvement in sorghum.

4.8 SOYBEANS

Soybeans are most commonly grown in rotation with corn and form an important rotational crop for wheat, cotton and other systems as well. Data presented here are from South Dakota, Nebraska, Minnesota, Iowa, Missouri, Arkansas, Mississippi, Illinois, Indiana, Ohio, Kentucky and North Carolina. Soybean acreage has increased over time in response to market signals and the expansion of corn acreage (see Section 4.2), while yields have also increased steadily (Figure 8a). Over the past several decades, GE herbicide tolerant seed has become predominant. A relatively complete set of data is available on chemical use in soybeans, and IPM practice data are available for four years, starting in 2012. As noted with other crops, soybean chemical use data do not account for seed-applied insecticides, which are in near universal use [107].

Soybeans are susceptible to damage and yield loss from multiple weed species, so herbicide tolerant varieties provide a strategy for effective weed management that also allows for soil conservation practices such as no-till production. In 2012, 40% of soybean acres were grown in no-till systems. In addition, the adoption of cover crops generally requires farmers to use an additional herbicide application to terminate the growth of the cover crop in the spring to prevent competition with soybeans.

However, as weeds have evolved resistance to the herbicides used with GE herbicide tolerant soybeans, seeds with tolerance for additional herbicide modes of action are increasingly being developed and adopted [124]. This has increased the volume of herbicide applied as multiple

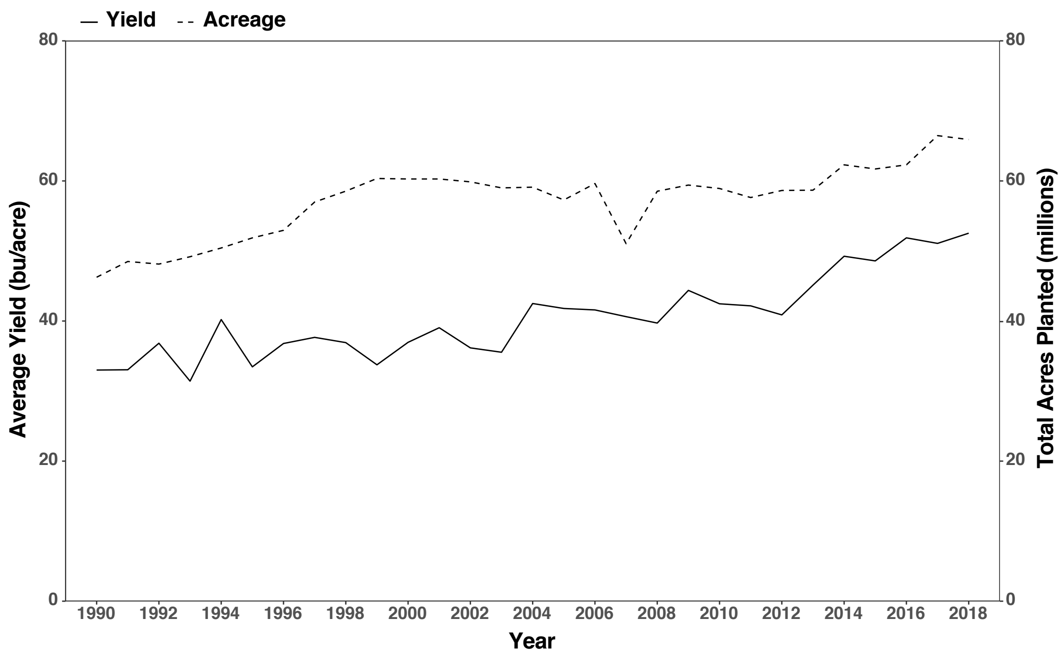

Figure 8a, Soybeans: Trends for average yield (solid line) and total planted area (dotted line) for soybeans for 1990−2018. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

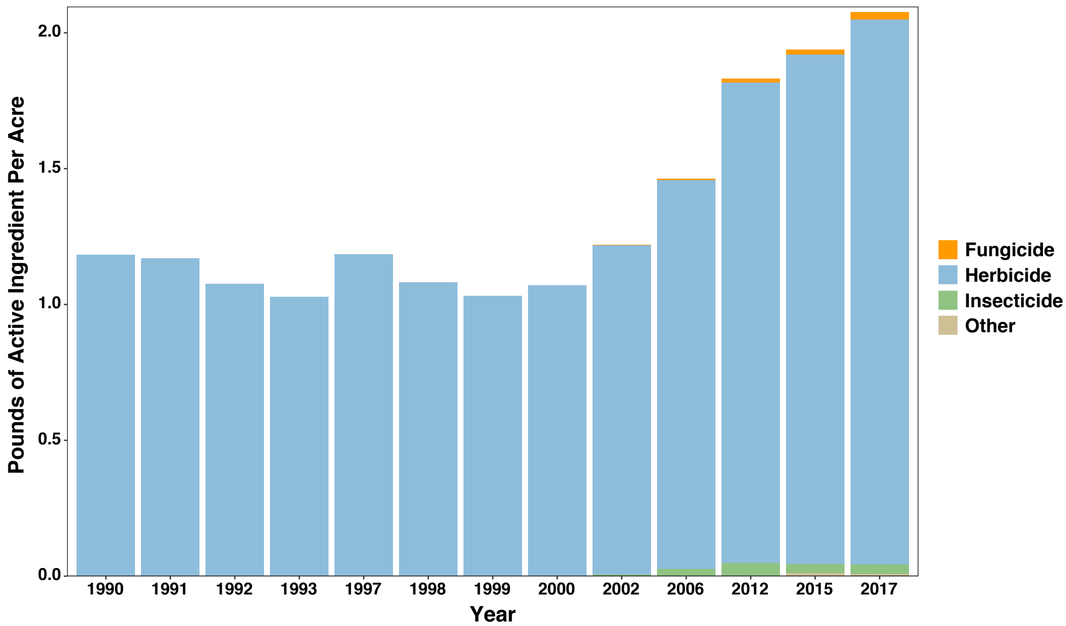

Figure 8b, Soybeans: Chemical use quantities of herbicides, insecticides, fungicides, and other crop protectants for soybeans adjusted for planted area. Seed−applied pesticides are not captured by USDA surveys and thus not included in the chemical use quantities. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

products may be needed to treat for weeds resistant to different chemicals (Figure 8b). Resistant-weed management has become a considerable concern for soybean farmers, and effective strategies to manage weeds are needed. While in the past, farmers have been able to count on introductions of new chemical herbicides with different modes of action that were generally less toxic and safer, no new modes have been discovered in 30 years, leading to increasing reliance on existing products that are increasingly less effective [60].

As soybeans are an important rotation crop with corn and with cotton, the use of the same herbicide mode of action across a rotation exacerbates the problem of resistant weeds. While there is a great deal of research underway, farmers must be vigilant and be prepared to be adaptive with management practices to respond to this challenge. Land-Grant Universities, supported by USDA and grower organizations, have collectively developed a Crop Protection Network web site for corn and soybeans to track threats to production as they emerge — currently available for disease and under development for weed and pests [125]. These types of resources can help growers diagnose the problem behind the damage on their fields and provide tools to assess individual risk to specific problems, helping farmers make decisions about when, whether and how to apply chemical control.

For insect management, soybeans provide an opportunity for growers to adopt IPM. The key soybean insect pest in the Upper Midwest is the soybean aphid. First reported in the United States at the turn of the century [126], the soybean aphid spread rapidly across the North Central soybean growing region [127]. Although the damage aphid infestations do to crop yield has varied year to year [128,129], the potential for yield loss adds pressure to producers when deciding their aphid management strategies [130]. Due to the presence of the aphid, soybean acres treated with insecticides in the United States increased from <1% in the year 2000 to over 13% in 2006 [131]. The most commonly used insecticide — neonicotinoid seed treatments, have been found to have limited effectiveness against aphids in some cases although they remain in widespread use [132,133]. Recent research has found that seed-applied insecticides may provide little financial or risk mitigation benefit to farmers [90]; however, as for corn, the treatments are

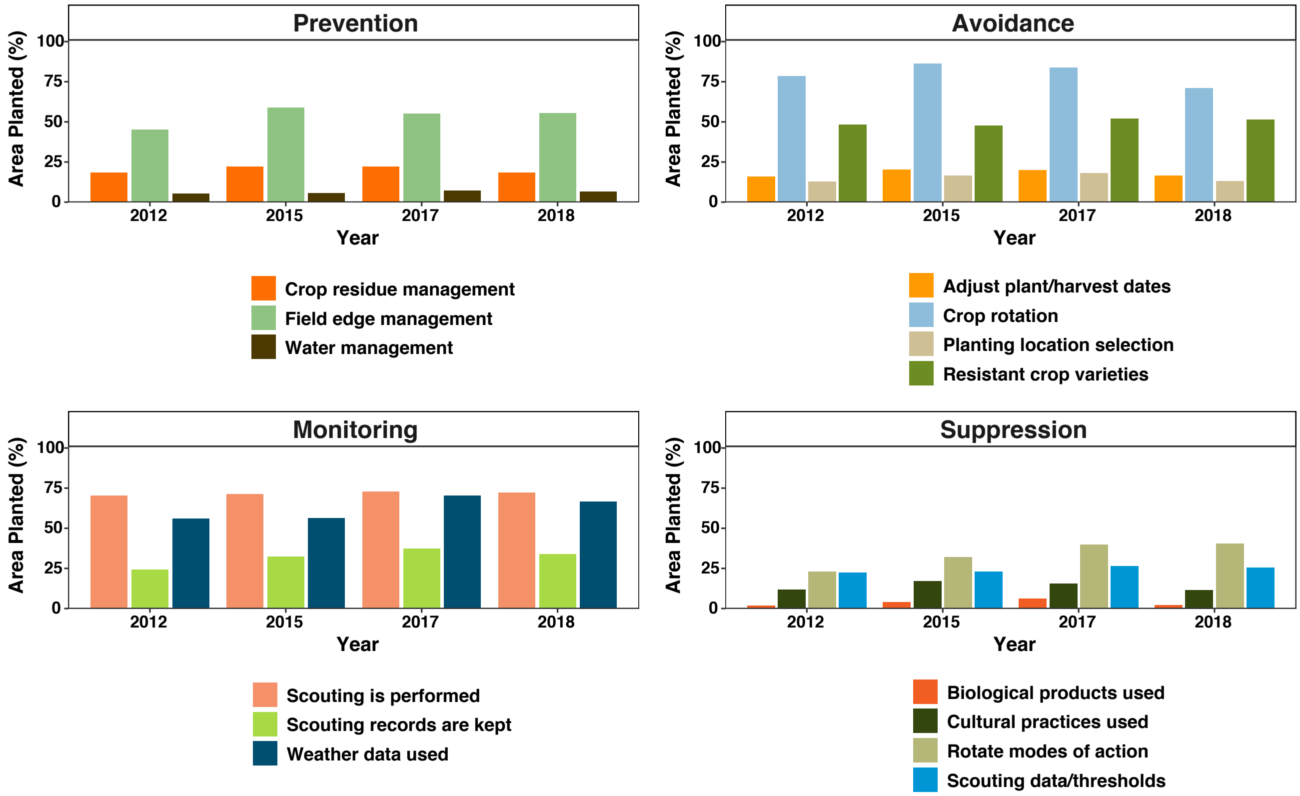

Figure 8c, Soybeans: Integrated Pest Management practice adoption for soybeans in percent of area planted and separated by strategy under the Prevention, Avoidance, Monitoring, and Suppression (PAMS) framework. Not all available IPM strategies were included. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

High Adoption (>40%)	Priorities for Adoption
▪ Crop rotation (Avoidance)	▪ Rotate modes of action (Suppression)
▪ Scouting is performed (Monitoring)	▪ Scouting records are kept (Monitoring)
▪ Weather data used (Monitoring)	▪ Cultural practices (Suppression)
▪ Field edge management (Prevention)	
▪ Resistant crop varieties (Avoidance)	

Figure 8d: IPM practices with relatively high adoption, and key opportunities identified for improvement in soybeans.

applied to seed at the supplier distribution center, so individual farmers may have limited choice based on what is available at their local retailer. These findings followed a statement from the U.S. Environmental Protection Agency that concluded neonicotinoid seed treatments provide few consistent production benefits to soybean farmers [91]. This presents an opportunity for greater IPM adoption, which could bring cost savings for soybean producers.

IPM practices that are most common in soybean include scouting and crop rotation, as well as planting of resistant crop varieties and management of field edges (Figure 8c). On average, however, only 34% of acres are reported as rotating modes of action of chemical control, which is a key strategy for managing herbicide resistant weeds, although there appears to be a slight increase in this practice in the last two years of IPM data.

4.9. WHEAT

Wheat acreage in the U.S. has declined in the past decade, but it remains one of the largest crops in terms of overall production in the United States. Wheat can be grown across much of the country — while cool temperatures are required, wheat can be planted in the spring in northern areas (spring wheat) or in the fall to experience cool winter temperatures in southern areas (winter wheat). For both winter and spring wheat, acreage has declined over the past several decades while yields have increased (Figures 9a, 10a). Seed-applied pesticides are not included in pesticide use data presented here, although they represent a common practice in wheat production. Spring wheat data presented here are from Montana, North and South Dakota and Minnesota, and winter wheat data are from Washington, Oregon, Idaho, Montana, South Dakota, Nebraska, Colorado, Kansas, Oklahoma, Texas, Missouri, Illinois and Ohio.

A primary driver of pesticide use for wheat is the disease referred to as Fusarium head blight (FHB) or scab. Management to control this disease is essential, as it can cause a toxin to develop in the wheat kernel that is harmful to humans and livestock, and therefore causes a total loss of the crop for the farmer, who cannot sell damaged wheat. Less severe damage can include lower yields and reductions in wheat quality that impact the marketability of the grain. FHB is managed through IPM practices and applications of fungicide.

FHB has been occurring more frequently since 2012, causing an increase in fungicide use (Figure 9b, 10b) due in part to the expansion of corn into northern regions with substantial wheat acreage. Corn is a host plant for FHB and has expanded northward as new varieties adapted to the region and market forces have made it an attractive option for farmers. However, corn residue can harbor FHB and infect wheat planted in the next season. Thus, one management technique to reduce risk of FHB is to plan the rotation so that wheat does not follow either corn or wheat. As FHB spores from corn residue or infected wheat can be wind transmitted across fields, management also requires vigilance in scouting of fields for signs of infection.

Wheat is also susceptible to damage from insect pests, the Hessian fly being one of the most destructive to production, and one for which several cultural practices have proven effective. The practice of planting wheat in the fall after Hessian fly activity stops due to cold weather, typically called a fly-free date, has been common in the Upper Midwest and Northern Great Plains since the early 1900s. Other cultural practices include the avoidance of wheat, barley, and rye (all Hessian fly hosts) as cover crops if planting before the fly-free dates, and planting wheat varieties bred to resist the fly damage [134].

Recommended IPM practices include scouting, planting resistant varieties of wheat, using tillage to incorporate residues, and using fungicides to control disease outbreaks. IPM practice data indicate high adoption rates for crop rotation as well as management at field edges and scouting (Figure 9c, 10c). Farmers can use the web resources made available by USDA and University experts [135] to find information on locally resistant varieties, news of outbreaks and other information on integrated management for FHB and forecasting models to determine risk of infection.

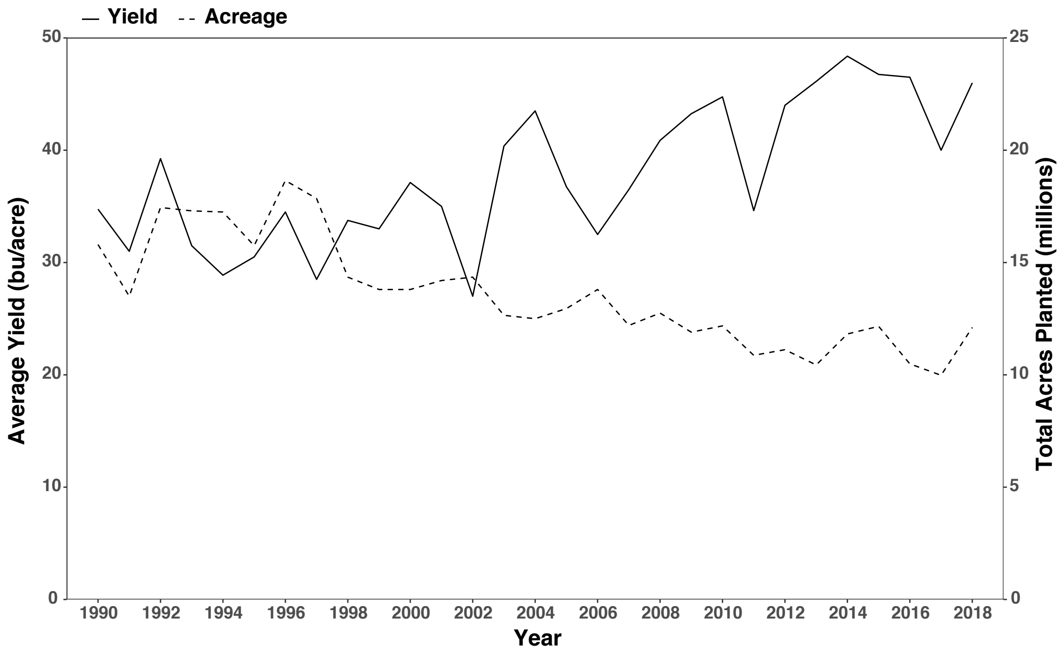

Figure 9a, Spring Wheat: Trends for average yield (solid line) and total planted area (dotted line) for spring wheat for 1990−2018. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

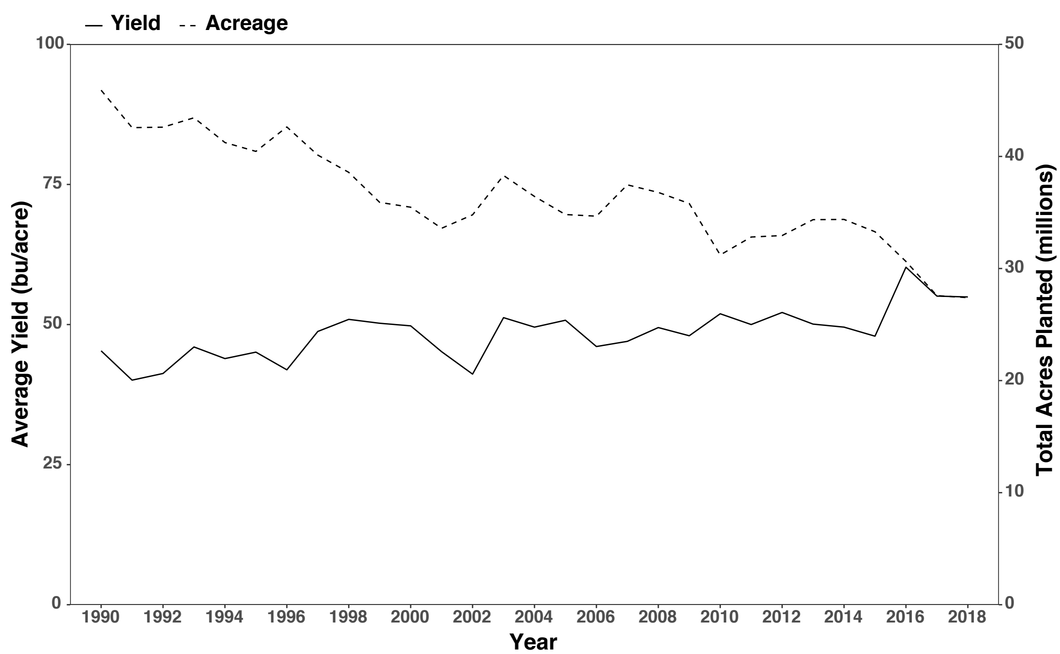

Figure 10a, Winter Wheat: Trends for average yield (solid line) and total planted area (dotted line) for winter wheat for 1990−2018. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

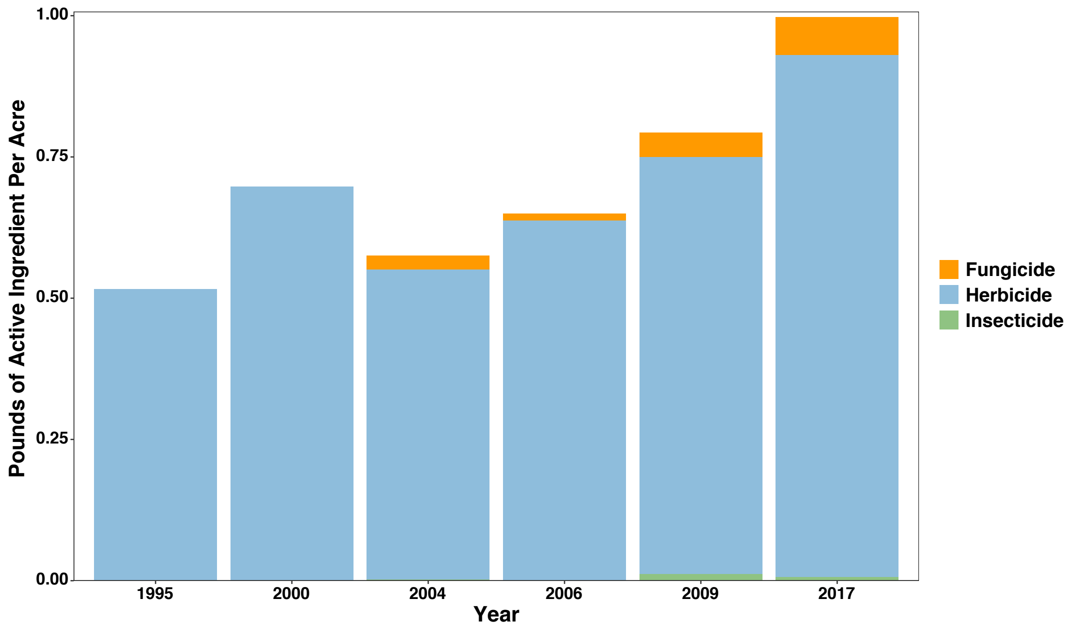

Figure 9b, Spring Wheat: Chemical use quantities of herbicides, insecticides, fungicides, and other crop protectants for spring wheat adjusted for planted area. Seed−applied pesticides are not captured by USDA surveys and thus not included in the chemical use quantities. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

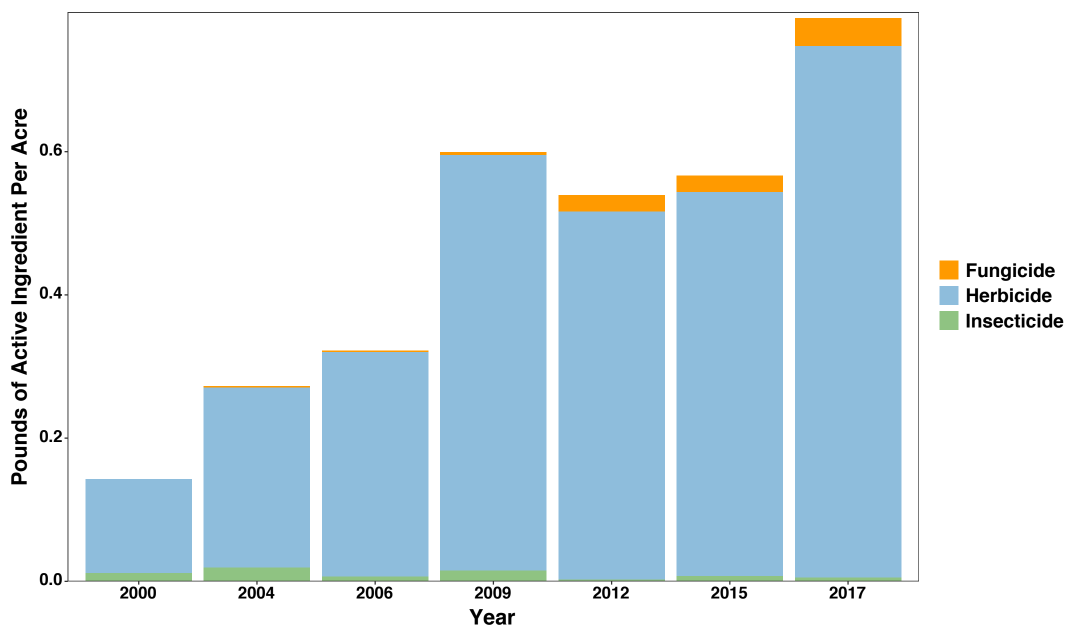

Figure 10b, Winter Wheat: Chemical use quantities of herbicides, insecticides, fungicides, and other crop protectants for winter wheat adjusted for planted area. Seed−applied pesticides are not captured by USDA surveys and thus not included in the chemical use quantities. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

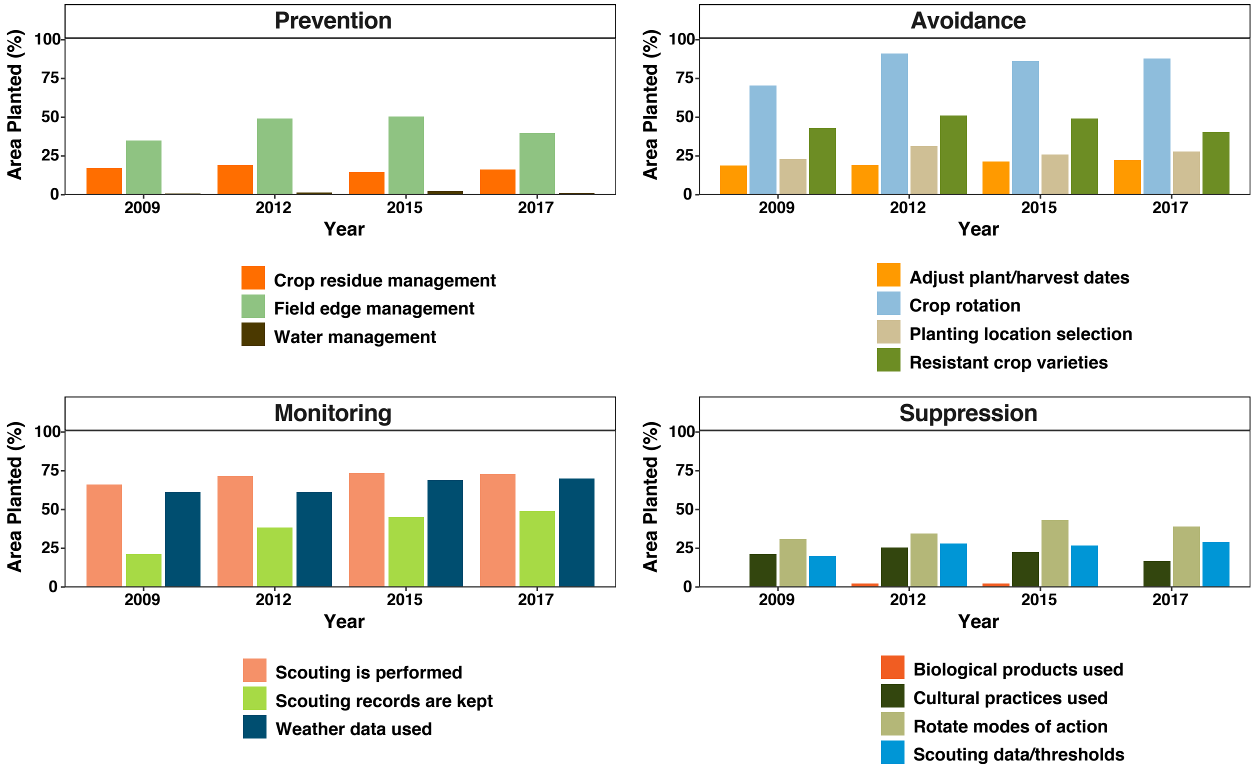

Figure 9c, Spring Wheat: Integrated Pest Management practice adoption for spring wheat in percent of area planted and separated by strategy under the Prevention, Avoidance, Monitoring, and Suppression (PAMS) framework. Not all available IPM strategies were included. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

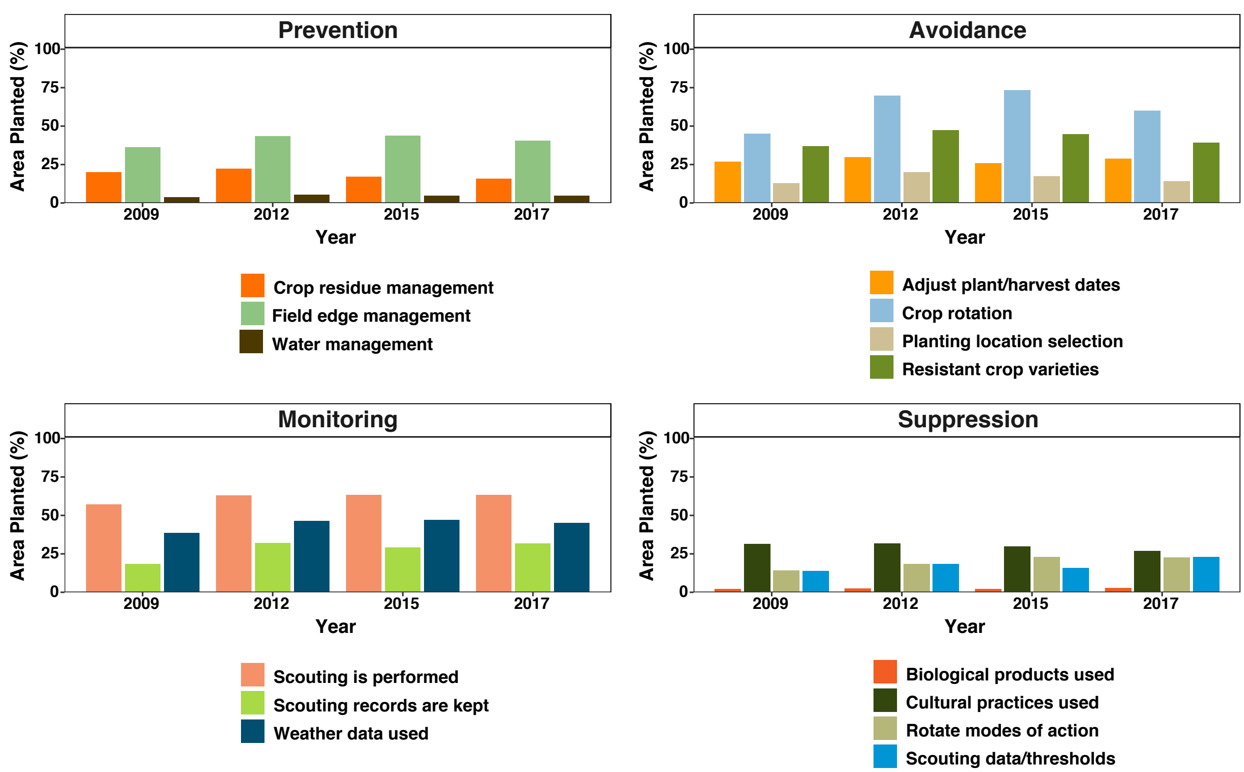

Figure 10c, Winter Wheat: Integrated Pest Management practice adoption for winter wheat in percent of area planted and separated by strategy under the Prevention, Avoidance, Monitoring, and Suppression (PAMS) framework. Not all available IPM strategies were included. Data from United States Department of Agriculture, National Agricultural Statistics Service, Quick Stats.

High Adoption (>40%)	Priorities for Adoption
Crop rotation (Avoidance)	Scouting records are kept (Monitoring)
Scouting is performed (Monitoring)	Crop residue management (Prevention)
Weather data used (Monitoring)	Scouting data/thresholds (Suppression)
Resistant crop varieties (Avoidance)	
Field edge management (Prevention)	

Figure 9d: IPM practices with relatively high adoption, and key opportunities identified for improvement in wheat.

4.10. Summary of Key Findings

There are five common themes that emerge from considering the research and data on chemical use and pest management practices across the nine commodity crops assessed.

1. The importance of diverse crop rotations that are carefully planned in order to break the cycle for specific pests is a clear finding from the analysis. Understanding of the full biological life cycle and disrupting pests with timely rotation of a non-host crop and related strategies, can reduce the incidence of damaging outbreaks that require chemical treatment on a farm or in a farming community. Diverse crop rotations also support other sustainable agriculture objectives, including improved soil health.

2. Critical to reducing the risk of pesticide resistance is rotating modes of action of the chemicals used. This is a very important factor for the largest-acreage crops, which rely on very few pesticide modes of action, across the country. This problem is compounded in common rotations where both crops are frequently treated with the same chemical modes of action (corn-soybean and cotton-soybean). Coordination across grower organizations to devise strategies for rotations is needed.

3. Crop varieties bred or engineered to have resistance to specific pest species and diseases can play an important role. This solution is not a panacea as the biology of certain crops or pests can make development of resistant varieties technically challenging. Research and development for resistant crop varieties should remain a priority.

4. Another common finding is that providing farmers with choice in the characteristics of seed to purchase is important. Farmers benefit from having multiple options for productive seeds adapted to their environmental conditions that also offer them better control over their pest management choices. For example, in regions where pests are developing resistance to seed treatment insecticides or to the Bt pesticidal effects, farmers need to have a choice of whether or not to plant seed with that pest control integrated (e.g., untreated or untraited seed) or whether to use other IPM practices to manage pests while interrupting the pest's development of resistance to those modes of action.

5. Finally, examples of successful community and region wide successes in advanced pest detection networks and reporting tools highlight the important role that Land-Grant Universities play in helping farmers manage pest, weed and disease outbreaks. Many have also invested in development of digital tools and field tests to help farmers more rapidly identify pest threats to production and target specific strategies for early mitigation. Such efforts should continue to be supported, enhanced and their availability and utility effectively communicated to farming communities.

5. Opportunities to Advance Responsible Pest Management

Considering both the scientific literature and what insights can be gleaned from the data and farmer experiences in the prior sections, we have outlined recommendations for how each sector of the value chain can contribute to advancing responsible pest management that supports resilient ecosystems and enhances farmer livelihoods.

- **Agribusiness** has a critical role to play in supplying farmers with effective approaches to manage pests. A critical missing element for producers of most commodities is choice. While not every contingency can be planned for, the current situation in most crops is that treatments are disproportionately skewed towards worst-case scenarios of pest infestations, particularly regarding insect and fungal pests. Specifically, diversification of pest management practices has become essential for successful farming but can remain challenging to adopt for many farmers. By evolving and expanding their business models to sell differently, agribusiness companies can provide agronomic advice, tools, technologies and services to support their customers in implementing responsible pest management.
  - Technologies are emerging that help farmers scout fields using drones along with handheld technology solutions that can be used to rapidly identify pest species in the field. These technologies are critical to better enable targeted control strategies and identify efficiencies that can be gained by not using chemical treatments in some areas, which can help ensure IPM is an affordable choice.
  - Another role for agribusiness is in the development of biopesticide options and targeted guidance for their use for specific pests. Providing biopesticide options that have demonstrated effectiveness in field trials is an important need to help manage pesticide resistance threats.
  - Providing a diversity of seed options for farmers in terms of the incorporated pest management traits and treatments to enable farmers to adopt IPM strategies that rotate the modes of action of pesticides.
  - Agribusinesses can also help to incentivize IPM by promoting solutions that work by targeting specific outbreaks as they occur rather than prophylactic treatments that may be costly and lack effectiveness.
- **Brands and Retail** companies have several important roles to play to support both their farmer suppliers and address their customers concerns about health and biodiversity.
  - A key challenge to farmers who are interested in planting a more diverse crop rotation is the availability of a market for the crop. Providing a demand signal for a more diverse array of crops would create more rotation options for farmers and enable greater IPM adoption. Companies can work with their supply chains to determine what rotational crops would be most beneficial for IPM adoption and related environmental goals such as improving soil health through regenerative farming practices and offering assistance in finding or creating markets to support farmers in growing diversified crops.

  - Companies can also partner with their suppliers to ensure that farmers from which they are sourcing have adequate access to and opportunities for education and technical assistance on IPM practice adoption.
  - Consumer-facing companies also have an important role to play in educating consumers. Helping consumers understand the challenges farmers face and the stewardship efforts they undertake to protect biodiversity and minimize environmental risk would help in creating a more informed public on the risks and benefits of chemical use in agriculture.
  - Brands and Retailers can also help promote responsible pest management by helping share in the agronomic and financial risk that farmers face to adopt regenerative agriculture practices that improve soil health, which also delivers co-benefits of increasing farmers' resilience against pest pressures.

- **Civil Society** has several important roles to play in ensuring public awareness and supply chain transparency on threats to biodiversity, aquatic ecosystems and human health.
  - Environmental organizations can play an important role in communication, as a voice trusted by the general public, to highlight environmental impacts and document progress towards protecting biodiversity.
  - Civil society can also underscore the importance of working lands as a critical partner in biodiversity conservation and help educate their constituents on the complexities facing farmers, which require decision-making and expertise in an array of topics.
  - Civil society can provide valuable scientific and agronomic input to supply chain efforts to adopt IPM practices and can also encourage and support supply chain efforts on transparency.
  - Civil society should continue to advocate for reducing the environmental risks of pesticide use, and devising and supporting mitigation strategies such as expanding pollinator habitat, and increasing the amount of refuge land in agricultural landscapes.

- **Grower** organizations representing the nation's farmers also have a role to play in advocating for collaborative approaches and frameworks to solve the challenges highlighted here.
  - By establishing community efforts to identify and combat pesticide resistance problems, grower organizations can help preserve the efficacy of and social license to utilize chemical pesticides that their members rely on.
  - Grower organizations can lead the way in working with agribusiness and brand and retail companies to ensure farmers have choice in terms of seeds, chemicals and market opportunities.
  - By helping to develop and identify cost-effective IPM alternatives to current prevailing chemical control programs, grower organizations can also support development of resources that will protect biodiversity, while also improving water quality and human health.

- **University and government** scientists and advisors provide critical independent advice to farmers and the value chain in finding solutions for responsible pest management. Scientists from Land-Grant universities and government agencies like the Natural Resources Conservation Service can play an important role by providing clear science-based guidance to farmers on how to integrate IPM practices for their specific situation and pest challenges. Assisted by technology, they can form communities across regions to share scouting information and assist farmers in early pest identification. Continued research in agricultural economics, entomology, weed science, rural sociology, and plant pathology is also critical for adapting management practices for effective pest control. All of these should be complemented by robust economic analyses.

Finally, all sectors can work together to advance collective action. Pest management is a community effort, and IPM practice adoption will be most effective when done in coordination among neighboring farmers and their support networks. All organizations with an interest in advancing responsible pest management can contribute by starting dialogues among farmers in a watershed or supply shed, providing educational resources and assistance specific to their pest management challenges, and working together to help meet the common goals of productive farmland and a healthy environment.

Many of the practices recommended in IPM align with practices considered important for other environmental sustainability goals. For example, diversification of crops in a rotation and inclusion of cover crops are strategies key for improving soil health as well as for avoidance of pest infestations. Using pesticides in a precise and judicious manner has myriad short and long term benefits for farmers and consumers alike. Advancing responsible pest management will take coordinated, collaborative action and commitment over time to work together in developing systems for profitable and sustainable farming systems that can successfully manage for pest problems with the least possible risk to environmental health, pest resistance development and human well-being.

We encourage all organizations to form partnerships with one another to advance common goals to preserve and protect biodiversity and improve water quality by adoption of responsible pest management in farming communities. Through projects enrolled in Field to Market's Continuous Improvement Accelerator, organizations have a consistent framework to assist them in developing continuous improvement goals and taking action to support farmers in improving environmental outcomes by adopting Integrated Pest Management strategies and other sustainability practices that build soil health and resilience to pest pressure. Together, farmers and the supply chain can explore solutions that support resilient ecosystems and enhance farmer livelihoods.

6. References Cited

1. Thomson AM, Ramsey S, Barnes E, Basso B, Eve M, Gennet S, Grassini P, Kliethermes B, Matlock M, McClellen E, et al.: **Science in the Supply Chain: Collaboration Opportunities for Advancing Sustainable Agriculture in the United States**. *Agric Environ Lett* 2017, **2**:6.

2. Thomson A, Ehiemere C, Carlson J, Matlock M, Barnes E, Moody L, DeGeus D: **Defining Sustainability as Measurable Improvement in the Environment: Lessons from a Supply Chain Program for Agriculture in the United States**. In *Sustainability Perspectives: Science, Policy and Practice*. Edited by Khaiter P, Erechtchoukova M. Springer Nature Switzerland; 2020:133–154.

3. Fernandez-Cornejo J, Nehring R, Osteen C, Wechsler S, Martin A, Vialou A: **Pesticide Use in U.S. Agriculture: 21 Selected Crops, 1960-2008**. *USDA Econ Inf Bull* 2014, **124**:86.

4. Perry E, Ciliberto F, Hennessy D, Moschini G: **Genetically engineered crops and pesticide use in U.S. maize and soybeans**. *Sci Adv* 2016, 2.

5. Fernandez-Cornejo J, Hallahan C, Nehring R, Wechsler S, Grube A: **Conservation tillage, herbicide use, and genetically engineered crops in the United States: The case of soybeans**. *AgBioForum* 2012, **15**:231–241.

6. Hartman Group: *Connecting Benefits with Values through Personal Consumption*. 2017.

7. IPBES: *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. 2019.

8. Dibartolomeis M, Kegley S, Mineau P, Radford R, Klein K: **An assessment of acute insecticide toxicity loading (AITL) of chemical pesticides used on agricultural land in the United**. *PLoS One* 2019, doi:10.1371/journal.pone.0220029.

9. Stern V, Smith R, Van den Bosch R, Hagen K: **The integration of chemical and biological control of the spotted alfalfa aphid: the integrated control concept**. *Hilgardia* 1959, **29**:81–101.

10. Yamamuro M, Komuro T, Kamiya H, Kato T, Hasegawa H, Kameda Y, Prefecture S: **Neonicotinoids disrupt aquatic food webs and decrease fishery yields**. *Science* 2019, **366**:620–623.

11. Hallmann CA, Foppen RP, van Turnhout CA, de Kroon H, Jongejans E: **Declines in insectivorous birds are associated with high neonicotinoid concentrations**. *Nature* 2014, **511**.

12. Gilliom RJ: **Pesticides in U.S. streams and groundwater**. *Environ Sci Technol* 2007, **41**:3409–3414.

13. Battaglin WA, Sandstrom MW, Kuivila KM, Kolpin DW, Meyer MT: **Occurrence of Azoxystrobin, Propiconazole, and Selected Other Fungicides in US Streams, 2005–2006**. *Water, Air, Soil Pollut* 2011, **218**:307–322.

14. Nowell LH, Moran PW, Schmidt TS, Norman JE, Nakagaki N, Shoda ME, Mahler BJ, Van Metre PC, Stone WW, Sandstrom MW: **Complex mixtures of dissolved pesticides show potential aquatic toxicity in a synoptic study of Midwestern US streams**. *Sci Total Environ* 2018, **613**:1469–1488.

15. Belden JB, Gilliom RJ, Martin JD, Lydy MJ: **Relative Toxicity and Occurrence Patterns of Pesticide Mixtures in Streams Draining Agricultural Watersheds Dominated by Corn and Soybean Production**. *Integr Environ Assess Manag* 2007, **3**:90–100.

16. Battaglin WA, Thurman EM, Kalkhoff SJ, Porter SD: **Herbicides and Transformation Products in Surface Waters of the Midwestern United States**. *J Am Water Resour Assoc* 2003, **39**:743–756.

17. U.S. Geological Survey: *The quality of our nation's waters - nutrients and pesticides. U.S. Geological Survey Circular 1225*. 1999.

18. Hladik ML, Kolpin DW, Kuivila KM: **Widespread occurrence of neonicotinoid insecticides in streams in a high corn and soybean producing region, USA**. *Environ Pollut* 2014, **193**:189–196.

19. Klarich KL, Nicholas CP, Dewald EM, Hladik ML, Kolpin DW, Cwiertny DM, Lefevre GH: **Occurrence of Neonicotinoid Insecticides in Finished Drinking Water and Fate during Drinking Water Treatment**. *Environ Sci Technol Lett* 2017, **4**:168–173.

20. National Research Council: *The impact of genetically engineered crops on farm sustainability in the United States*. The National Academies Press; 2010.

21. Conley S, Krupke CH, Santini J, Shaner G: **Pest Management in Indiana Soybean Production Systems**. *J Ext 2007*, **45**.

22. Twenge JM, Campbell WK, Carter NT: **Declines in Trust in Others and Confidence in Institutions Among American Adults and Late Adolescents, 1972–2012**. *Psychol Sci* 2014, doi:10.1177/0956797614545133.

23. Lipset SM, Schneider W: **The Decline of Confidence in American Institutions**. *Polit Sci Q* 1983, **98**:379.

24. Kruger J, Dunning D: **Unskilled and Unaware of It : How Difficulties in Recognizing One's Own Incompetence Lead to Inflated Self-Assessments**. *J Pers Soc Psychol* 1999, **77**:1121–1134.

25. Levay K, Hendricks R, Volmert A: *The Landscape of Public Thinking about Farming*. 2018.

26. Belson NA: **US Regulation of Agricultural Biotechnology: An Overview**. *AgBioForum* 2000, **3**:268–280.

27. United States Environmental Protection Agency: **Data Requirements for Pesticide Registration**. 2019.

28. McDougall P: *The Cost of New Agrochemical Product Discovery, Development and Registration in 1995, 2000, 2005-8 and 2010-2014*. 2016.

29. United States Environmental Protection Agency: **Summary of the Food Quality Protection Act**. 2019.

30. Sparks TC, Lorsbach BA: **Perspectives on the agrochemical industry and agrochemical discovery**. *Pest Manag Sci* 2017, **73**:672–677.

31. Thayer K, Houlihan J: *Pesticides, Human health and the Food Quality Protection Act*. 2004.

32. United States Environmental Protection Agency: *Voluntary Reduced-Risk Pesticides Initiative. Pesticide Regulation (PR) Notice 93-9*. 1993.

33. United States Environmental Protection Agency: *Current and Previously Registered Section 3 Plant-Incorporated Protectant (PIP) Registrations*. 2018.

34. Office of Inspector General: *Impact of EPA's Conventional Reduced Risk Pesticide Program Is Declining. Report No. 14-P-0322*. 2014.

35. US EPA: *Inert Ingredients Eligible for FIFRA 25 (b) Pesticide Products*. 2016.

36. Tinsworth R: **Expedited registration review in the USA: The EPA's reduced risk program**. *J Environ Monit* 2000, **2**:63–68.

37. United States Government Accountability Office: *EPA Should Take Steps to Improve Its Oversight of Conditional Registrations*. GAO-13-145; 2013.

38. Sass J, Wu M: **Superficial safeguards: most pesticides are approved by flawed EPA process**. *NRDC Issue Br* 2013.

39. Lau J: **Nothing but Unconditional Love for Conditional Registrations: The Conditional Registration Loophole in the Federal Insecticide, Fungicide, and Rodenticide Act**. *Environ Law* 2014, **44**:1177–1202.

40. USEPA Office of Pesticide Programs: *Conditional Registration — Summary of OPP's Implementation of GAO's Recommendations*. 2014.

41. US EPA: **Schedule for Review of Neonicotinoid Pesticides**. 2019,

42. Davis AS, Frisvold GB: **Are herbicides a once in a century method of weed control?** *Pest Manag Sci* 2017, **73**:2209–2220.

43. Benbrook CM: **Impacts of genetically engineered crops on pesticide use in the U.S. — the first sixteen years**. *Environ Sci Eur* 2012, **24**:1–13.

44. Hellerstein D, Vilorio D, Ribaudo M: **Agricultural Resources and Environmental Indicators, 2019**. *USDA Econ Inf Bull* 2019, **208**:142.

45. Werle R, Oliveira MC, Jhala AJ, Proctor CA, Rees J, Klein R: **Survey of Nebraska Farmers' Adoption of Dicamba-Resistant Soybean Technology and Dicamba Off-Target Movement**. *Weed Technol* 2018, **32**:754–761.

46. Bish MD, Farrell ST, Lerch RN, Bradley KW: **Dicamba losses to air after applications to soybean under stable and nonstable atmospheric conditions**. *J Environ Qual* 2019, **48**:1675–1682.

47. Douglas M, Tooker J: **Large-Scale Deployment of Seed Treatments Has Driven Rapid Increase in Use of Neonicotinoid Insecticides and Preemptive Pest Management in U.S. Field Crops**. *Environ Sci Technol* 2015, **49**.

48. Douglas MR, Sponsler DB, Lonsdorf E V., Grozinger CM: **Rising insecticide potency outweighs falling application rate to make US farmland increasingly hazardous to insects**. *bioRxiv* 2019, doi:10.1101/715763.

49. Hurley TM: **Shock and Awe Pest Management: Time for Change**. *Choices* 2016, **31**:1–8.

50. Kniss AR: **Long-term trends in the intensity and relative toxicity of herbicide use**. *Nat Commun* 2017, **8**:1–7.

51. Goulson D: **An overview of the environmental risks posed by neonicotinoid insecticides**. *J Appl Ecol* 2013, **50**:977–987.

52. Roy CL, Coy PL, Chen D, Ponder J, Jankowski M: **Multi-scale availability of neonicotinoid-treated seed for wildlife in an agricultural landscape during spring planting**. *Sci Total Environ* 2019, **682**:271–281.

53. Berheim EH, Jenks JA, Lundgren JG, Michel ES, Grove D, Jensen WF: **Effects of Neonicotinoid Insecticides on Physiology and Reproductive Characteristics of Captive Female and Fawn White-tailed Deer**. *Sci Rep* 2019, **9**:1–10.

54. Eng ML, Stutchbury BJM, Morrissey CA: **A neonicotinoid insecticide reduces fueling and delays migration in songbirds**. *Science* 2019, **365**:1177–1180.

55. Meehan TD, Werling BP, Landis DA, Gratton C: **Agricultural landscape simplification and insecticide use in the Midwestern United States**. *Proc Natl Acad Sci* 2011, **108**:11500–11505.

56. Osteen CD, Fernandez-cornejo J: **Herbicide Use Trends : A Backgrounder**. *Choices* 2016, **31**:1–7.

57. Heap I: **International Survey of Herbicide Resistant Weeds**. *Weed Sci* 2019.

58. Shergill L, Barlow B, Bish M, Bradley KW: **Investigations of 2,4-D and Multiple Herbicide Resistance in a Missouri Waterhemp (Amaranthus tuberculatus) Population**. *Weed Sci* 2018, **66**:386–394.

59. Dentzman K, Gunderson R, Jussaume R: **Techno-optimism as a barrier to overcoming herbicide resistance: Comparing farmer perceptions of the future potential of herbicides**. *J Rural Stud* 2016, **48**:22–32.

60. Westwood JH, Charudattan R, Duke SO, Steven A, Marrone P, Westwood JH, Charudattan R, Duke SO, Fennimore SA, Marrone P, et al.: **Weed Management in 2050: Perspectives on the Future of Weed Science**. *Weed Sci* 2017, **66**:275–285.

61. Dentzman K: **Herbicide resistant weeds as place disruption: Their impact on farmers' attachment, interpretations, and weed management strategies**. *J Environ Psychol* 2018, **60**:55–62.

62. Miranowski JA: **Intervention to Manage Pest Resistance: Community-Based or Government Regulation**. *Choices* 2016, **31**:1–8.

63. Huseth A, Chappell T, Chitturi A, Jacobson A, Kennedy G: **Insecticide Resistance Signals Negative Consequences of Widespread Neonicotinoid Use on Multiple Field Crops in the U.S. Cotton Belt**. *Environ Sci Technol* 2018, **52**:2314–2322.

64. Mallet J: **The evolution of insecticide resistance: Have the insects won?** *Trends Ecol Evol* 1989, **4**:336–340.

65. Ervin D, Frisvold GB: **Are Community-Based Approaches to Manage Herbicide Resistance Wisdom or Folly?** *Choices* 2016, **31**:1–8.

66. Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, et al.: **Reducing the Risks of Herbicide Resistance : Best Management Practices and Recommendations.** *Weed Sci* 2012, doi:10.1614/WS-D-11-00155.1.

67. Frisvold GB, Ervin DE, Osteen CD, Fernandez- J, Jussaume R, Hurley TM, Ervin D, Frisvold GB: **Theme Overview: Herbicide Resistance Management**. *Choices* 2016, **31**:1–4.

68. Jussaume R, Dentzman K: **Farmers' Perspectives on Management Options for Herbicide-Resistant Weeds**. *Choices* 2016, **31**:1–7.

69. Marrone PG: **Pesticidal natural products–status and future potential**. *Pest Manag Sci* 2019, **75**:2325–2340.

70. Seiber JN, Coats J, Duke SO, Gross AD: **Biopesticides: state of the art and future opportunities**. *J Agric Food Chem* 2014, **62**:11613–11619.

71. United States Environmental Protection Agency: **What are Biopesticides?** 2016.

72. United States Environmental Protection Agency: **Fact Sheet for Limonene**. 1994.

73. United States Environmental Protection Agency: **Potassium bicarbonate (073508) and Sodium bicarbonate (073505) Fact Sheet Summary**. 2004.

74. Sporleder M, Lacey LA: **Biopesticides**. *In Insect Pests of Potato*. Elsevier; 2013:463–497.

75. Leahy J, Mendelsohn M, Kough J, Jones R, Berckes N: **Biopesticide oversight and registration at the U.S. Environmental Protection Agency**. *ACS Symp Ser* 2014, **1172**:3–18.

76. Marrone PG: **Barriers to adoption of biological control agents and biological pesticides**. In *Integrated Pest Management: Concepts, Tactics, Strategies and Case Studies*. Edited by Radcliffe EB, Hutchison WD, Cancelado RE. Cambridge University Press; 2009:163–178.

77. Smith RF, Apple JL, Bottrell DG: **The Origins of Integrated Pest Management Concepts for Agricultural Crops**. *Integr Pest Manag* 1976, doi:10.1007/978-1-4615-7269-5_1.

78. Ehler LE: **Integrated pest management (IPM): definition, historical development and implementation, and the other IPM**. *Pest Manag Sci* 2006, **62**:787–789.

79. Gray M, Ratcliffe S, Rice M: **The IPM paradigm: concepts, strategies and tactics**. In *Integrated Pest Management: Concepts, Tactics, Strategies and Case Studies*. Edited by Radcliffe, E., Hutchison, W., Cancelado R. Cambridge University Press: Cambridge, U.K.; 2009:1–13.

80. Smith RF, Smith GL: **Supervised control of insects: Utilizes parasites and predators and makes chemical control more efficient**. *Calif Agric* 1949, **3**:3–12.

81. Smith RF, Allen WW: **Insect Control and the Balance of Nature**. *Sci Am* 1954, **190**:38–43.

82. Smith RA, Reynolds HT: **Principles, definitions and scope of integrated pest control**. In P*roceedings of the FAO Symposium on Integrated Pest Control*. 1965:11–17.

83. National Academy of Sciences: **Integrated Systems of Pest Management**. In *Insect-Pest Management and Control*. The National Academies Press; 1969:447–449.

84. Kogan M: **Integrated pest management: historical perspectives and contemporary developments**. *Annu Rev Entomol* 1998, **43**:243–270.

85. Prokopy R, Kogan M: **Integrated pest management**. In *Encyclopedia of insects*. Elsevier; 2009:523–528.

86. Coble HD, Ortman EE: **The USA national IPM road map**. In *Integrated Pest Management: Concepts, Tactics, Strategies and Case Studies*. Edited by Radcliffe EB, Hutchinson WD, Cancelado RE. Cambridge University Press: Cambridge, U.K.; 2009:471–472.

87. United States Congress: *Testimony of Carol M. Browner, Administrator EPA; Richard Rominger, Deputy Secretary of Agriculture; and David Kessler, Commissioner of FDA. Hearings before the Committee on Labor and Human Resources, U.S. Senate, and Subcommittee on Health and the Enviro*. 1993.

88. United States Department of Agriculture: **The practice of integrated pest management (IPM**). **The PAMS approach**. 1993.

89. United States General Accounting Office: *Agricultural pesticides: Management improvements needed to further promote integrated pest management*. U.S. Government Printing Office, Washington, DC; 2001.

90. Mourtzinis S, Krupke CH, Esker PD, Varenhorst A, Arneson NJ, Bradley CA, Byrne AM, Chilvers MI, Giesler LJ, Herbert A, et al.: **Neonicotinoid seed treatments of soybean provide negligible benefits to US farmers**. *Sci Rep* 2019, **9**:1–7.

91. USEPA: **Benefits of neonicotinoid seed treatments to soybean production**. *Off Chem Saf Pollut Prev Memo* 2014.

92. **National Roadmap for Integrated Pest Management**. In *4th National Integrated Pest Management Symposium Proceedings*. 2003:9–11.

93. United States Department of Agriculture: **A National Road Map for Integrated Pest Management**. 2018.

94. Pedigo L: **Closing the gap between IPM theory and practice**. *J Agric Entomol* 1995, **12**:171–181.

95. Ehler LE, Bottrell DG: **The illusion of integrated pest management**. *Issues Sci Technol* 2000, **16**:61–64.

96. Mortensen DA, Bastiaans L, Sattin M: **The role of ecology in the development of weed management systems: An outlook**. *Weed Res* 2000, **40**:49–62.

97. Anderson RL: **A multi-tactic approach to manage weed population dynamics in crop rotations**. *Agron J* 2005, **97**:1579–1583.

98. Peterson RKD, Higley LG, Pedigo LP: **Whatever Happened to IPM?** *Am Entomol* 2018, **64**:146–150.

99. Herbert DA: **Integrated Pest Management Systems : Back to Basics to Overcome Adoption Obstacles**. *J Agric Entomol* 1995, **12**:203–210.

100. Ostrom E: **A General Framework for Analyzing Sustainability of Social-Ecological Systems**. *Science* 2009, **325**:419–422.

101. Ervin DE, Breshears EH, Frisvold GB, Hurley T, Dentzman KE, Gunsolus JL, Jussaume RA, Owen MDK, Norsworthy JK, Mahmud M, et al.: **Farmer Attitudes Toward Cooperative Approaches to Herbicide Resistance Management : A Common Pool Ecosystem Service Challenge**. *Ecol Econ* 2019, **157**:237–245.

102. Iles A, Marsh R: **Nurturing diversified farming systems in industrialized countries: How public policy can contribute**. *Ecol Soc* 2012, **17**.

103. Hendrickson MK, James HS: **The ethics of constrained choice: How the industrialization of agriculture impacts farming and farmer behavior**. *J Agric Environ Ethics* 2005, **18**:269–291.

104. United States Department of Agriculture: **The practice of integrated pest management (IPM)**. **The PAMS approach**. 1993.

105. National Agricultural Statistics Service: **United States Summary and State Data**. *2017 Census Agric* 2019, **1**:820.

106. Penn State Extension: *Barley Yellow Dwarf Vectors*. 2013.

107. Douglas MR, Tooker JF: **Large-Scale Deployment of Seed Treatments Has Driven Rapid Increase in Use of Neonicotinoid Insecticides and Preemptive Pest Management in U.S. Field Crops**. *Environ Sci Technol* 2015, **49**:5088–5097.

108. Tooker JF, Douglas MR, Krupke CH: **Neonicotinoid Seed Treatments: Limitations and Compatibility with Integrated Pest Management**. *Agric Environ Lett* 2017, **2**:1.

109. DuPont Pioneer Agronomy Sciences: **Plan to scout for corn rootworm**. *Michigan Farm News* 2018.

110. Alford A, Krupke CH: **A Meta-analysis and Economic Evaluation of Neonicotinoid Seed Treatments and Other Prophylactic Insecticides in Indiana Maize From 2000-2015 With IPM Recommendations**. *J Econ Entomol* 2018, **111**:689–699.

111. Sappington TW, Hesler LS, Clint Allen K, Luttrell RG, Papiernik SK: **Prevalence of sporadic insect pests of seedling corn and factors affecting risk of infestation**. *J Integr Pest Manag* 2018, 9.

112. CDRC: *Corn Dust Research Consortium (CDRC) Final Report*. 2015.

113. Krupke CH, Hunt GJ, Eitzer BD, Andino G, Given K: **Multiple routes of pesticide exposure for honey bees living near agricultural fields**. *PLoS One* 2012, **7**.

114. Szczepaniec A, Raupp MJ, Parker RD, Kerns D, Eubanks MD: **Neonicotinoid Insecticides Alter Induced Defenses and Increase Susceptibility to Spider Mites in Distantly Related Crop Plants**. *PLoS One* 2013, **8**.

115. Douglas MR, Rohr JR, Tooker JF: **Neonicotinoid insecticide travels through a soil food chain, disrupting biological control of non-target pests and decreasing soya bean yield**. *J Appl Ecol* 2015, **52**:250–260.

116. Cook D, Cutts M: *Cotton Insect Losses 2018*. 2018.

117. Reisig DD, Kurtz R: **Bt Resistance Implications for Helicoverpa zea (Lepidoptera: Noctuidae) Insecticide Resistance Management in the United States**. *Environ Entomol* 2018, **47**:1357–1364.

118. Thiessen L, Rivera Y: *Root Knot Nematode of Cotton*. 2019.

119. Schnepf R: *U.S. Peanut Program and Issues*. 2016.

120. Sorensen RB, Brenneman TB, Lamb MC: **Peanut Yield Response to Conservation Tillage, Winter Cover Crop, Peanut Cultivar, and Fungicide Applications**. *Peanut Sci* 2010, **37**:44–51.

121. Brandenburg R, Jordan D, Shew B, Wilcut J, Toth S: *Crop Profile for Peanuts in North Carolina*. 2005.

122. USDA-NASS: **Potatoes 2017 summary**. *United States Dep Agric Natl Agric Stat Serv* 2018.

123. Smith D, Anisco J: **Sorghum in Texas: Crop Brief on Production, Pests and Pesticides**. 2000,

124. Kniss AR: **Genetically Engineered Herbicide-Resistant Crops and Herbicide-Resistant Weed Evolution in the United States**. *Weed Sci* 2018, **66**:260–273.

125. Land Grant Universities: **Crop Protection Network**. *https://cropprotectionnetwork.org* 2019.

126. Kilman S: **Chinese aphids menace Midwest's soybean crop**. *Wall Str J* 2000, **17**.

127. Ragsdale DW, Voegtlin DJ, Neil RJO: **Soybean Aphid Biology in North America**. *Ann Entomol Soc Am* 2004, **92**:204–208.

128. Rice ME, O'Neal ME, Pedersen P: *Soybean Aphids in Iowa — 2007*. 2007.

129. O'Neal ME: *Insecticide use for soybean aphid control up again in 2005*. 2005.

130. Hodgson EW, Mccornack BP, Tilmon K, Knodel JJ: **Management Recommendations for Soybean Aphid (Hemiptera: Aphididae) in the United States**. *J Integr Pest Manag* 2012, **3**:1–10.

131. Ragsdale DW, Landis DA, Brodeur J, Heimpel GE, Desneux N: **Ecology and Management of the Soybean Aphid in North America**. *Annu Rev Entomol* 2011, **56**:375–399.

132. Krupke CH, Alford A, Cullen E, Hodgson E, Knodel J, McCornack B, Potter B, Soigler M, Tilmon K, Welch K: **Assessing the value and pest management window provided by neonicotinoid seed treatments for management of soybean aphid (Aphis glycines Matsumura) in the Upper Midwestern United States**. *Pest Manag Sci* 2017, **73**:2184–2193.

133. Hesler LS, Allen KC, Luttrell RG, Sappington TW, Papiernik SK: **Early-season pests of soybean in the United States and factors that affect their risk of infestation**. *J Integr Pest Manag* 2018, **9**.

134. Schmid RB, Knutson A, Giles KL, Brian P: **Hessian Fly (Diptera : Cecidomyiidae) Biology and Management in Wheat**. *J Integr Pest Manag* 2018, **9**:1–12.

135. US Wheat and Barley Scab Initiative: **ScabSmart**. *https://scabsmart.org* Accessed: September, 2019.

Appendices

Appendix A: Glossary of Terms

1. **Cultural controls**: Practices that modify the crop environment to reduce pest establishment, reproduction, dispersal or survival. Examples include crop rotation and modifying irrigation practices.

2. **Exposure**: One of two main factors used to assess the risk of a chemical, exposure refers to the likelihood of coming into contact with a specific chemical through direct contact, drift, or residues.

3. **Field edge management**: Practices intended to mitigate pest incidence and/or damage to crops by manipulating the areas bordering crop fields to reduce suitability for pests. Practices can be cultural or chemical, and examples include mowing, chopping or plowing field edges, or chemical applications to control weeds or host species to insects or disease pests. Field edges may also provide habitat for beneficial insects.

4. **Fungicide**: Chemicals that kill fungal diseases.

5. **Genetically engineered (GE)**: Refers specifically to traits added to crops using genetic engineering technology as opposed to traditional plant breeding. Commercial GE crops in the U.S. discussed in this report include corn, soybean, sugar beet and cotton.

6. **Herbicide**: Chemicals intended to kill or damage weeds. May be used to terminate cover crops and as a harvest aid (desiccant or defoliant of cash crops to facilitate equipment operation in the field).

7. **Integrated Pest Management (IPM**): A science-based decision-making process that identifies and reduces risks from pests and pest management related strategies. IPM coordinates the use of pest biology, environmental information, and available technology to prevent unacceptable levels of pest damage by the most economical means, while minimizing risk to people, property, resources, and the environment.

8. **Insecticide**: Chemicals intended to impact insect pests.

9. **Mode of action**: Refers to how a particular chemical pesticide operates on the target pest. The Insecticide Resistance Action Committee (IRAC), Fungicide Resistance Action Committee (FRAC) and Herbicide Resistance Action Committee (HRAC) classify insecticides, fungicides and herbicides, respectively, by modes of action. Rotating chemical modes of action or combining multiple modes of action in a single application, are primary strategies to delay the evolution of resistant pests.

10. **Pesticide**: General term referring to a formulated chemical containing an active ingredient designed to kill, repel or otherwise suppress populations or activity of a particular pest or group of pests. Encompasses herbicides, insecticides, fungicides, soil fumigants, miticides, rodenticides and other chemicals designed to control pests.

11. **Plant-incorporated pesticide**: Refers to a toxin present in a genetically engineered crop plant that suppresses insect pests. For example, Bt corn and Bt cotton are plants genetically engineered to include the Bacillus thuringiensis toxin which kills immature insects (larvae) feeding on the crop.

12. **Resistance trait**: A genetic trait or set of traits that provide a crop variety with the ability to withstand attack by a pest, disease or pesticide and remain virtually unaffected. May be bred traditionally or genetically engineered or arise inadvertently within a plant or pest population.

13. **Resistant pests**: Weeds, insects or other pests that have naturally evolved genetic resistance to specific chemical compounds or chemical modes of action after repeated exposure to the same chemical.

14. **Risk**: A risk framework accounts for multiple factors such as exposure and toxicity to assess the overall threat a chemical poses to specific human or environmental health outcomes.

15. **Scouting**: Systematic inspection of crop fields to evaluate plant health, identify threats and inform treatment decisions. Scouting can include counting pests or pest-damaged plants or plant parts, checking insect or disease spore traps, using drones to visually survey remote parts of fields, etc.

16. **Seed treatment**: A seed coated with a chemical pesticide to combat soil diseases and pests.

17. **Soil fumigant**: Chemicals used to treat soils to combat soil pests such as nematodes, rootworms and soil-borne diseases that infect or damage crop roots.

18. **Toxicity**: A major factor used in the assessment of risk, toxicity refers to how potent a chemical is, which impacts the level of exposure that may lead to harm.

Appendix B: States Included in Data Analysis by Crop

Table: States included in the analysis for each crop. We included only states where data were available in all years to ensure continuity and consistency in the trends analysis. Tables 1 and 2 indicate what years data are available for each crop.

Crop	States Included														
Barley	CA	ID	MN	MT	ND	PA	WA	WI							
Corn	IL	IN	IA	KS	KY	MI	MN	MO	NE	NC	OH	PA	SD	TX	WI
Cotton	AL	AR	GA	MS	MO	NC	TN	TX							
Peanuts	AL	GA	NC	TX											
Potatoes	CO	ID	ME	MI	MN	ND	WA	WI							
Rice	AR	CA	LA	MS	TX										
Sorghum	CO	KS	NE	OK	SD	TX									
Soybeans	AR	IL	IN	IA	KY	MN	MS	MO	NE	NC	OH	SD			
Spring Wheat	MN	MT	ND	SD											
Winter Wheat	CO	ID	IL	KS	MO	MT	NE	OH	OK	OR	SD	TX	WA		

Appendix C: IPM Practice Categories and Descriptions

Table: PAMS category and description for each practice label included in the figures in this document. Note that some practices were aggregated into broader categories for this analysis.

Category	Practice Label	Description of Practice
Prevention	Crop residue management	Crop residues removed or burned down
	Field edge management	Field edges, ditches, or fence lines were chopped, sprayed, mowed, plowed, or burned
	Crop residue management	Plowed down crop residue using conventional tillage
	Water management	Irrigation scheduling used to avoid situations conducive to disease development
Avoidance	Resistant crop varieties	Crop or plant variety chosen for specific pest resistance
	Planting location selection	Planting locations planned to avoid cross infestation of pests
	Adjust plant/harvest dates	Planting or harvesting dates adjusted
	Crop rotation	Rotated crops during past 3 years
Monitoring	Scouting is performed	Scouted — established process used
	Scouting is performed	Scouted for diseases
	Scouting is performed	Scouted for insects & mites
	Scouting is performed	Scouted for weeds
	Weather data used	Weather data used to assist decisions
	Scouting records are kept	Written or electronic records kept to track the activity of pests
Suppression	Cultural practices used	Beneficial organisms applied or released
	Biological products used	Biological pesticides applied
	Cultural practices used	Ground covers, mulches, or other physical barriers maintained
	Rotate modes of action	Pesticides with different mechanisms of action used to keep pest from becoming resistant to pesticides
	Scouting data/thresholds	Scouting data compared to published information to assist decisions
	Cultural practices used	Trap crop grown to manage insects

Field to Market®

777 N. CAPITOL STREET NE, SUITE 802 | WASHINGTON, DC 20002

WWW.FIELDTOMARKET.ORG