IN THE WEEDS

Understanding the Impact of GE Crops on Pesticide Use

CENTER FOR
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Public Interest

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Table of Contents

Executive Summary

A Google search for "GMOs and pesticides" generates over 1.6 million hits. Pick an article at random and you will likely find one of two theses:

> **1) GMOs increase the use of pesticides** by creating crops designed to withstand indiscriminate spraying of herbicides (pesticides used to destroy weeds), or
>
> **2) GMOs decrease the use of pesticides** by eliminating the need for insecticides (pesticides used to repel insects) and increasing efficiency of production.

Both types of articles may reference the same datasets, often from the United States Department of Agriculture (USDA) or the United States Environmental Protection Agency (EPA). Both may appear in reputable news sources or even scientific journals. Yet somehow these two seemingly contradictory messages persist.

This report explores the complexity of the much-discussed but little-understood question of the impact of genetically engineered (GE) crops on farmers' use of pesticides. First, we will provide some background on what defines a pesticide and why they are used. Next, we will examine trends in pesticide use and adoption of GE crops over time. We pose specific questions regarding trends in pesticide use:

- Which GE crops might have an impact on which pesticides?
- How has the adoption of insect-resistant crops impacted the use of insecticides?
- How has the adoption of herbicide-tolerant crops impacted the use of herbicides?

We then answer these questions based on the latest available data. Finally, we discuss emerging trends impacting pesticide use in GE crops.

Our analysis concludes that the impacts of GE crops on pesticide use must be considered on a case-by-case basis: crop by crop and pesticide by pesticide, with particular attention to substitution effects and their implications for the net toxicity of pesticides applied to each crop. We find that the adoption of GE corn and cotton with traits for insect resistance has helped significantly reduce the use of insecticides on these crops. GE crops that are herbicide tolerant have altered the types of herbicides used, with a dramatic increase in glyphosate use, and a decrease in some more acutely toxic herbicides (such as atrazine) in corn, cotton, and soybeans.

Since glyphosate-tolerant crops were first adopted, the net acute toxicity of all herbicides applied to U.S. crops (as determined by the acute mammalian toxicity of each herbicide in use weighted by the volume of its use each year) has decreased in corn and cotton, and both chronic and acute toxicity have decreased in soy. However, chronic herbicide toxicity has risen in corn and cotton, which is largely attributable to the increased use of glyphosate.

With increasing adoption of new crop varieties engineered to tolerate herbicides with higher toxicities, overall herbicide toxicity must be carefully monitored in the coming years. Farmers and GE crop developers should proceed cautiously in order to prevent the spread of herbicide resistant weeds and resistant pests which threaten to undermine the advances made by the adoption of GE crops.

Pesticides: What and Why

Pesticides are substances used to destroy or repel pests.[1] Pesticides may be used to repel insect pests (in which case they are called insecticides), weeds (herbicides), fungi (fungicides), or other organisms considered harmful to cultivated plants or agriculture. This report will focus on insecticides and herbicides because there are GE crops designed to impact their use. By definition, pesticides are intended to be harmful to some organisms.[2] A pesticide is considered effective when it can eliminate a pest without significantly damaging the crop.

Pesticides are one of several pest management tools that farmers use to prevent crop loss and increase the efficiency of crop production. They help farmers provide us with produce with no signs of damage by insects. They also allow farmers to eliminate weeds without hand-weeding their fields or tilling their soil, which increases efficiency while helping to prevent soil erosion caused by tillage. Contrary to common belief, they are used in both conventional and organic agriculture.[3] The major difference in pesticide use between conventional and organic agriculture is that organic farmers are, in most cases, only permitted to use pesticides derived from naturally-occurring chemicals, whereas conventional farmers may use a broader range of synthetic chemical pesticides.

Chemical pesticides have been used in U.S. agriculture since the 19th century, when farmers began applying heavy metals such as copper, lead, and arsenic (*e.g.,* in the form of copper sulfate, lead arsenate, sodium arsenite, and cupric acetoarsenite, or “Paris green”) to their fields.[4] As new chemical formulations were developed in the 20th century, use of chemical pesticides increased and became nearly ubiquitous in certain crops.

By the late 1950s, public concern about pesticide safety began to rise, and in 1962, Rachel Carson’s book *Silent Spring* mobilized a public outcry against the indiscriminate use of pesticides.[5] This led to the establishment of the U.S. Environmental Protection Agency (EPA) in 1970 which quickly banned several highly toxic pesticides. Such concern also led to the development of biopesticides, pesticides derived from natural sources such as animals, plants, bacteria, and certain minerals.[6]

Bacillus thuringiensis (*Bt*)—a bacterium found in soil— was the first biological agent harnessed by scientists to produce a bioinsecticide.[7] Insecticide sprays containing *Bt* have been used in U.S. agriculture since 1958[8] and continue to be widely used, owing their success to *Bt*'s ability to produce toxins that target specific insects with no major risks to humans and other non-target organisms.

In the mid-1990s, scientists began introducing GE crop varieties that incorporate genes from *Bt* bacteria, allowing the plants to produce the insecticidal compounds in their tissues instead of being applied externally.[9] These incorporated genes are called plant incorporated protectants (PIPs) and are regulated by EPA as pesticides.[10] Examples of PIP-producing crops grown in the U.S. include insect-resistant corn, cotton, and soybean engineered with *Bt* genes, and virus-resistant papaya and potato engineered with plant virus coat protein genes that imbue resistance to plant viruses.[11]

Bt genes are more effective at combating insects than *Bt* sprays across the plant's lifespan. *Bt* sprays are quickly disabled after exposure to sunlight and wash away quickly in rain.[12] *Bt* crops also eliminate the need for farmers to buy and apply *Bt* sprays, saving farmers time and money.

In a separate development around the same time, scientists began introducing GE crop varieties that can tolerate the application of broad-spectrum herbicides that target a wide variety of weeds, but which spare the crop.[13] This allowed specific herbicides to be applied to crops throughout their lifecycle, as needed. Examples of herbicide-tolerant crops grown in the U.S. include glyphosate-tolerant corn, soybean, cotton, sugar beet, canola, and alfalfa; and glufosinate-tolerant corn, soybean, cotton, and canola.[14]

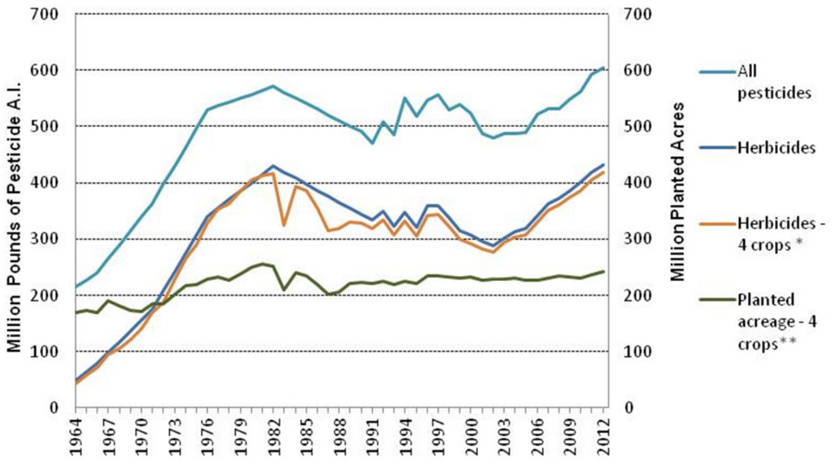
Today, all pesticides used in U.S. agriculture, including PIPs, must be registered with EPA. The agency assesses the safety of each formulation based on risks to human and ecological health, requires extensive safety labeling with directions on approved uses, and conducts health and environmental risk assessments, with additional considerations for PIPs, such as allergenicity.[15,16,17]

Pesticide Use Over Time

Volume Trends

Trends in pesticide use are typically displayed in annual lbs of pesticide active ingredient (a.i.) applied, or annual lbs a.i. per acre. USDA data from 1964 through 2012 reveal that overall pesticide use (in lbs a.i.), including herbicides, insecticides, and fungicides, increased rapidly in the 1960s and 70s, fluctuated throughout the 1980s and 90s, and increased from the mid-2000s to early 2010s (Figure 1). Meanwhile, planted acreage of the top four U.S. crops (corn, cotton, soybeans, and wheat) remained steady from the early 1990s to the early 2010s.

Figure 1. Pesticide and Herbicide Use, and Crop Acreage, 1964-2012



Source: USDA data in Osteen & Fernandez-Cornejo (2016)
*4 crops = corn, cotton, soybeans, and wheat
Herbicide use for corn, cotton, soybeans, and wheat, corrected for crop acreage.
Excludes petroleum distillates, sulfur, and sulfuric acid.

A major contributor to the increase in volume of pesticides applied from the mid-2000s to early 2010s was an increase in applications of herbicides, notably glyphosate. Overall, glyphosate use in U.S. agriculture skyrocketed from 7.4 million lbs a.i. in 1990 to nearly 250 million lbs a.i. in 2014.[18] Glyphosate use also increased in proportion to total herbicide use during this time, accounting for 34%, 70%, and 37% of total pounds of herbicide applied per acre on corn, soybeans, and cotton, respectively, in 1991, to 46%, 92%, and 76%

in 2005, and 45%, 74%, and 55% in 2014.[19] Glyphosate is appealing to farmers because it is inexpensive, easy to use, kills a broad spectrum of weeds, and breaks down quickly in the environment. It also has significantly lower acute and chronic toxicity than many other herbicides on the market.[20]

Glyphosate-tolerant crops were the first GE herbicide-tolerant varieties, introduced in 1996 and still popular today.[21] Increasing use of glyphosate has taken place in GE glyphosate-resistant crops like soybean, corn, and cotton, as well as in crops with no GE varieties such as wheat, barley, and oranges.[22] Specifically, from 1990 to 2014, glyphosate applications increased in GE glyphosate-resistant soybeans, corn, and cotton by a factor of 46, 78, and 91, respectively, and in non-GE oranges, spring wheat, and barley by a factor of 2, 47, and 81, respectively.[23]

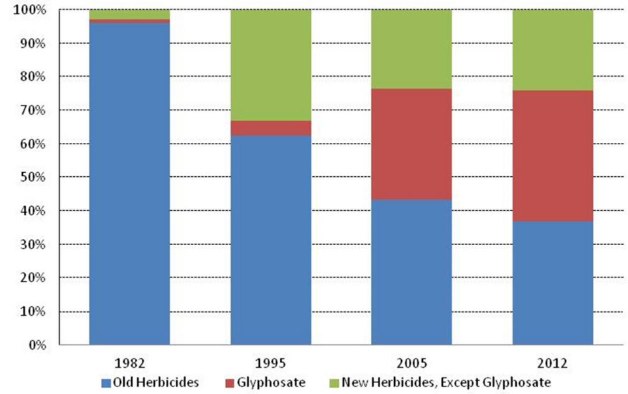
Figure 1 shows that use of herbicides in U.S. agriculture as a whole has risen since the early 1990s, and that four crops—corn, cotton, soybeans, and wheat—account for the vast majority of that increase. Notably, while the majority of the corn, cotton, and soybean crop was GE herbicide-tolerant varieties by the early 2000s, there is no GE wheat planted in the U.S. yet.

The high rates of glyphosate use in non-GE crops reveal that trends in herbicide use on GE herbicide-tolerant crops reflect patterns of use across U.S. agriculture, and cannot be entirely attributed to the introduction of GE technology. It is clear that the introduction of glyphosate-tolerant varieties has contributed to an increased volume of glyphosate use on those crops.[24] However, as discussed below, a more important consideration than change in volume is change in the overall toxicity of the mix of herbicides farmers used with the introduction of these GE crops.

Substitution Effects

Most farmers used pesticides long before GE crops came into the picture. In 1996, when GE crops were first available and adoption was still low, 97 percent of corn acres, 97 percent of soybean acres, and 92 percent of cotton acres were treated with herbicides.[25] For these farmers, the introduction of GE crops did not affect *whether or* *not* they used pesticides, but rather *which* pesticides they used (and how much).

Figure 2. Glyphosate as a Percentage of Herbicide Acre-Treatments* on Corn, Cotton, Soybeans, and Wheat, 1982-2012



Source: Osteen & Fernandez-Cornejo (2016)
*An acre-treatment is one acre treated with an herbicide multiplied by average number of applications per acre. This measure emphasizes the relative proportion of are treated with pesticides, accounting for multiple treatments and herbidices per acre.

The effects of increased or decreased use of one pesticide on net toxicity depends on which new chemicals or farming practices replace it. As an example, the data on substitution effects of glyphosate tell a complicated story. While glyphosate substituted for other herbicides in the cases of corn, soybean, cotton, and wheat (Figure 2), overall herbicide application (lbs a.i./ acre) has decreased for corn but increased for cotton and soybean since the introduction of GE varieties.[26]

These volume trend data can be useful in helping us understand trends in agricultural production practices and types of pesticides used over time. However, their utility in demonstrating the implications of pesticide use on human and environmental health (and, therefore, in understanding the impact of adopting GE crops) is limited. As noted by USDA in a recent environmental impact statement:

> *[I]n regard to potential harms to humans and wildlife, pesticide use data commonly referred to in the lay and peer reviewed literature citing the weight or volume of pesticide used conveys little meaningful information without understanding the toxicity of the pesticide being discussed, which varies widely among the pesticides used.*[27]

A pound of one pesticide may be very different in terms of risks to human and environmental health compared to a pound of a different pesticide. For this reason, a better way to measure the impact of pesticide use and how it has changed over time is by assessing toxicities and comparing volumes weighted by their relative toxicities over time.

Measuring Toxicity

> "Citing the weight or volume of pesticide used conveys little meaningful information without understanding the toxicity of the pesticide being discussed"
> -USDA APHIS, 2019

The EPA considers both acute (short-term) and chronic (long-term) toxicity of individual pesticides to a wide range of species as part of its risk assessment and approval process.[28,29,30] Based on these assessments, the agency sets tolerances, or legal limits, for the level of a given pesticide that may be applied to each crop as well as allowable limits for pesticide residues in food.[31,32] EPA also assigns each pesticide a toxicity category (I through IV) with different protective requirements for farmers and farmworkers handling the chemicals.[33]

Toxicity is less commonly used than weight or volume in describing trends in pesticide use over time because it is a more complex measure. Measuring toxicity may require an assessment of impacts on various species, through multiple pathways (*e.g.*, oral, inhalation, dermal), and findings depend on the dose, duration, and frequency of exposure. Unfortunately, there is no scientific consensus on the best method for assessing overall toxicity in order to compare multiple pesticides. Several studies have applied a measure called the environmental impact quotient (EIQ), which takes into account a wide range of pesticide properties including toxicity to non-target organisms such as birds, fish, and bees, and mammals, as well as soil behavior and persistence, but this measure, particularly when applied to herbicides, has faced harsh criticism from some biologists and weed scientists as overly reliant on difficult-to-verify assumptions and no better than measuring "pounds on the ground."[34,35]

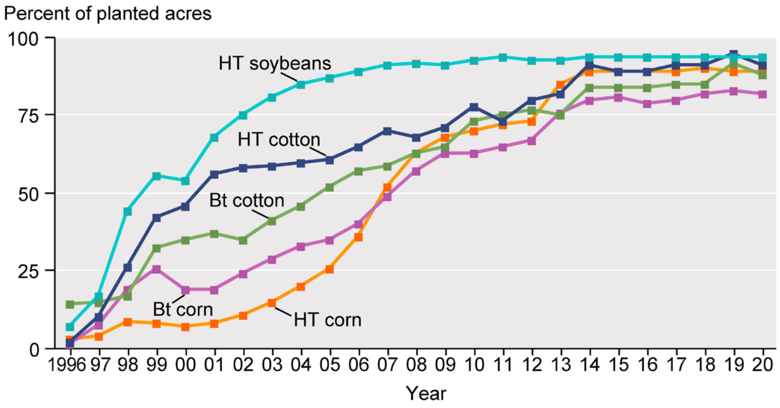
A different approach called hazard quotient or risk quotient assessment looks separately at the chronic hazard and acute hazard quotients using evidence from mammalian toxicity studies as a proxy for human toxicity.[36] This approach is favored by EPA[37] and the European Food Safety Agency.[38] Weed scientist Andrew Kniss used this approach to analyze changes in overall toxicity of herbicides applied to six crops (corn, soybean, cotton, rice, spring wheat, and winter wheat) from 1990 to 2015.[39] His analysis provides a nuanced answer to the question of how the adoption of GE crops has impacted herbicide use. We will rely on this analysis for understanding the impact of the adoption of GE herbicide-tolerant crops on human health and safety.

Adoption of GE Crops Over Time

There are 10 crops with GE varieties currently grown and sold in the U.S.: alfalfa, apples, canola, corn, cotton, papaya, potatoes, soybeans, summer squash, and sugar beets.[40] Of these ten crops, six have been engineered with traits for herbicide tolerance (corn, soybean, cotton, canola, alfalfa, sugar beet), two have traits for insect resistance (corn, cotton), and four have traits such as disease resistance or non-browning (papaya, squash, apple, potato).

Observing the trajectory of adoption of GE crop varieties in the U.S. is critical to understanding which trends in pesticide use are associated with (or may even be attributed to) the use of these crops. Figure 3 demonstrates that by the early 2010s, nearly all of the millions of planted acres of corn, cotton, and soybeans were herbicide-tolerant varieties, and the majority of cotton and corn acres were engineered with *Bt* traits for insect resistance as well.[41] Specifically, the percent of soybean acres planted with herbicide-tolerant seed plateaued at a high of 94 percent in 2014.[42] Herbicide-tolerant corn reached 89 percent in 2020 and herbicide-tolerant cotton reached 95 percent in 2019.[43] Meanwhile, *Bt* corn and cotton acreage were at 82 percent and 88 percent in 2020.[44]

Figure 2. Adoption of Genetically Engineered Corn and Cotton in the United States, 1996-2019



Source: USDA (2020)
HT = Herbicide-tlerant
Bt = Bacillus thuringiensis

Herbicide-tolerant canola and sugar beets have also been almost ubiquitously adopted, with 95 percent of canola acres and 99 percent of sugar beet acres planted with herbicide-tolerant seed by 2013.[45] Alfalfa herbicide-tolerant varieties were only planted on 13 percent of alfalfa acres by 2013.[46]

The remaining GE crops currently grown in the U.S. are planted on only a small number of acres. As of 2017, there were about 6,000 acres of GE potatoes, 2,500 acres of GE summer squash, 1,000 acres of GE papaya, and 250 acres of GE apples grown in the U.S.[47] This is equivalent to less than one percent of the potato and apple acres, about seven percent of summer squash acres, and 35 percent of papaya acres grown in the U.S.[48]

Asking the Right Questions

Sweeping statements that GE technology has increased or decreased pesticide application are often substantiated with data referencing one specific crop (*e.g.,* corn) and/or one specific pesticide (*e.g.,* glyphosate). But the complete picture is much more complex. No blanket statement can be made regarding the impact of GE technology on pesticide application in agriculture overall. Instead, the effects must be evaluated on a case-by-case basis. This means considering the question of impact crop-by-crop, trait-by-trait, and pesticide-by-pesticide.

Crop-by-Crop

Importantly, our inquiry into the impact of GE crops on pesticide use can only be relevant to crops with varieties that been engineered to express traits relevant to pest management. Attributing any trends in herbicide and insecticide application to adoption of GE technology is only logical for crops with insect resistance and herbicide tolerance. This includes *Bt* corn and cotton, and herbicide-tolerant corn, cotton, soybean, canola, sugar beet, and alfalfa. Future GE crops engineered with antifungal properties may also prove to impact the use of fungicides. The GE *Phytophthora infestans*-resistant potato has also shown promise for reducing use of fungicide application to control foliar late blight disease, but this crop has not yet been commercialized.[49] However, there is no reason to believe that traits like the non-browning characteristic engineered in GE apples and potatoes would impact pesticide use.

Additionally, since pesticide use data are not typically separated by their applications to GE versus non-GE crops, trends can only be interpreted for crops which have near-complete adoption of GE varieties. Of the six herbicide-tolerant and/or insect-resistant crops, this excludes alfalfa (only 13% was GE in 2013) but includes canola (95% GE),[50] sugar beets (99% GE),[51] and corn, soybean, and cotton (each over 90% GE).[52] But even with the remaining five, it is important to be cautious when attributing trends in herbicide use to the adoption of GE crops since farmers have faced other changes over the past three decades in addition to adoption of GE technology that effect pesticide applications (*e.g.,* changes in climate, pesticide prices, pest populations, and weed resistance).

Trait-by-Trait

Next, the question must be framed according to the trait. For corn and cotton, which have widely adopted insect-resistant varieties, the question to ask is: "How has adoption of these GE crops impacted use of *insecticides*?" For corn, cotton, soybean, canola, and sugar beet, herbicide-tolerant seed is ubiquitously used, so the question is "How has adoption of these GE crops impacted the use of *herbicides*?"

Pesticide-by-Pesticide

Finally, particularly for herbicide-tolerant varieties, it is important that our questions consider the relevant pesticides. USDA has approved GE varieties with tolerance to different herbicides including glyphosate, glufosinate, 2,4-D, and dicamba. Each variety may therefore be associated with different pesticide tradeoffs, as farmers determine how to most efficiently eliminate weeds. To maximize efficiency of their pesticide use, for both financial and environmental reasons, farmers will trade off one pesticide for another. For example, glyphosate-tolerant corn may use more glyphosate but less dicamba. Likewise, dicamba-tolerant corn may use more dicamba but less glyphosate. Pesticide use data specific to the particular crop variety (*e.g.*, glyphosate-tolerant corn vs. glufosinate-tolerant corn) are not often available. But we can at least narrow our question further by asking, for example, "How has adoption of herbicide-tolerant GE crops impacted the use of glyphosate, glufosinate, 2,4-D, and dicamba, and have these pesticides replaced or supplemented others?"

BOX 1. DATA LAG

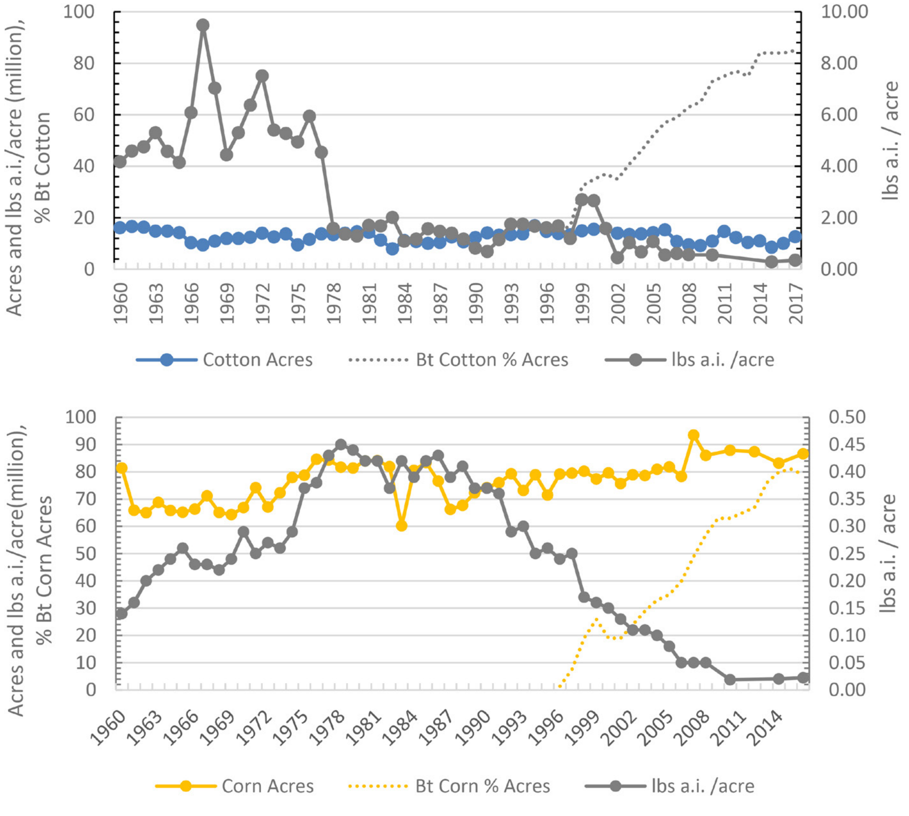
Unfortunately, pesticide use data lags about five to ten years behind actual use, so it's hard to know the latest trends. For this reason, we will only explore trends related to the first generation of widely-adopted GE crops in this report—*Bt* corn and cotton, and glyphosate-tolerant corn, cotton, and soybean.

Once more data are available, it will be particularly important to monitor the impact of adoption of dicamba- and 2,4-D-tolerant crops, as these herbicides have significantly higher toxicities than glyphosate.

GE Crops and Insecticide Use

The effects of insect-resistant crops on insecticide use are cut and dried in at least one respect. There has been a clear decrease in overall insecticide application since the introduction of insect-resistant corn and cotton, both in lbs and lbs/acre. A downward trend in insecticide use began in the 1970s, before GE crops with PIPs were first introduced in the 1990s, as EPA banned several highly toxic synthetic insecticides and companies began developing new insecticides that were effective at much lower doses.[53] But the introduction of GE *Bt* crops has brought insecticide use on corn and cotton to near all-time lows of 0.02-0.03 lbs a.i./acre (corn) and 0.29-0.35 lbs a.i./acre (cotton) (Figure 4).[54] With crops producing their own *Bt* toxins which are highly effective at killing targeted pests, there is no need to spray the chemical and microbial insecticides that previously targeted these pests. Figure 5 shows substantial decreases in applications of the insecticides chlorpyrifos, terbufos, and several others in corn during the period when *Bt* corn became widely adopted by U.S. farmers. Based on these trends, and similar trends in cotton, the National Academies of Science, Engineering, and Medicine concluded that, "In all cases examined, use of *Bt* crop varieties reduced application of synthetic insecticides in those fields."[55] Some of these synthetic insecticides had high acute and chronic toxicities,[56] whereas the *Bt* crops that replaced them are not known to be toxic to humans.[57] Therefore, it is clear that the adoption of *Bt* varieties has reduced both the volume and toxicity of insecticide applications in U.S. corn and cotton.

Figure 4. Rates of Insecticide Application in US Cotton (1960-2014) and Corn (1960-2017)



Source: Fernandez-Cornejo et al. (2014) & USDA-NASS (2018) in USDA APHIS (2019)- fig 3-16.

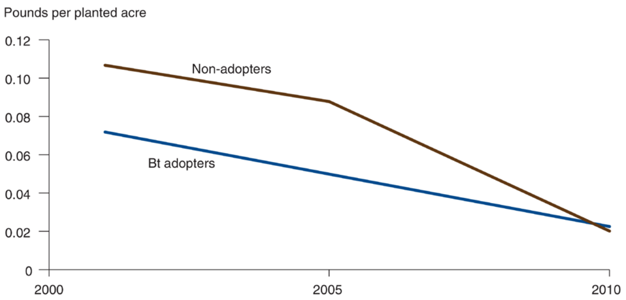
Figure 5. Major Insecticides Used on Corn in 2001 and 2005

	AREA APPLIED		TOTAL APPLIED	
	Percent		*Thousand Pounds*	
Active Ingredient	**2001**	**2005**	**2001**	**2005**
Bifenthrin	2	2	67	72
Carbofuran	*	*	476	113
Chlorpyrifos	4	2	3,663	2,047
Cyfuthrin	4	7	16	38
Dimethoate	*	*	164	68
Esfenvalerate	*	*	1	8
Fipronil	3	1	259	88
Lambda-cyhalothrin	2	1	23	25
Methyl parathion	1	*	386	82
Permethrin	3	1	236	116
Propargite	*	*	156	289
Tebupirimphos	4	6	371	573
Tefluthrin	6	7	466	637
Terbufos	3	*	2,491	331
Petroleum Distillate	*	N/A	56	N/A
Phorate	*	N/A	73	N/A
Zeta-cypermethrin	N/A	*	N/A	11
Other	N/A	N/A	100	351
Total			**8,904**	**4,498**
Planted acres (in thousands)			76,470	70,745

Source: USDA (2002, 2006) in Fernandez-Cornejo & Wechsler 2012
*Area applied is less than one percent.

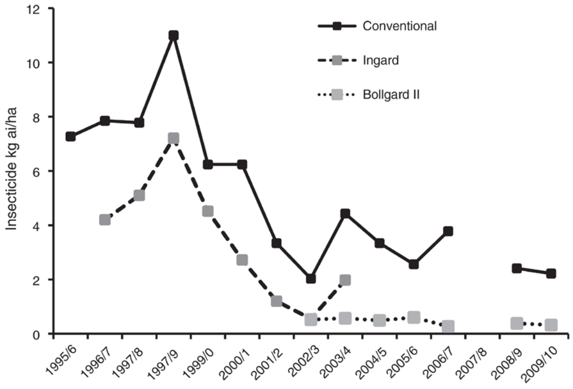
The adoption of *Bt* crops has even led to decreases in chemical insecticide use by farmers growing non-GE crops (or "non adopters"). For example, adoption of *Bt* corn in the U.S. (*see* Figure 3) has coincided with regional declines in European corn borer populations among both adopters and nonadopters of GE corn varieties, leading to lower insecticide use rates even by non-adopters (Figure 6). In addition, non-GE cotton growers in Australia have benefited from regional declines in pest populations (such as European corn borer, corn earworm, and pink bollworm) resulting from adoption of *Bt* cotton and so have reduced their insecticide use as well (Figure 7).[58] Even growers of vegetables like peppers, green beans, and sweet corn, for which there are no GE varieties, have seen pest declines which have been attributed to adoption of *Bt* crops at surrounding farms (Figure 8).

Figure 6. Rates of insecticide application by adopters and nonadapters of *Bt* corn in the U.S.



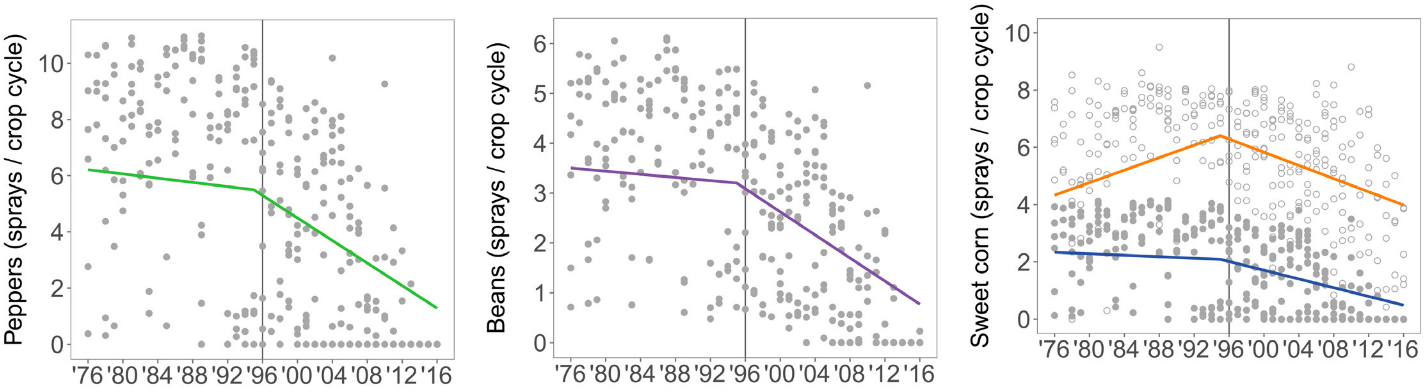
Source: Fernandez-Cornejo et al. (2014)

Figure 7. Rates of insecticide application by adopters and nonadapters of *Bt* cotton in Australia



Source: Wilson et al. (2013)
Conventional = non-GE; Ingard = *Bt* variety; Bollgard II = *Bt* variety

Figure 8. Trends in recommended insecticidal sprays to control European corn borer and corn earworm in vegetable crops (peppers, beans, and sweet corn) of Mid-Atlantic U.S., 1976-2016



Source: Dively et al. (2018)
Grey dots represent recommended insecticidal sprays based on moth captures recorded by 189 blacklight traps placed over 58,600 km^2 moth captures in each year were used to estimate
Graph for sweet corn includes lines demonstrating trends in two different species of moth

GE Crops and Herbicide Use

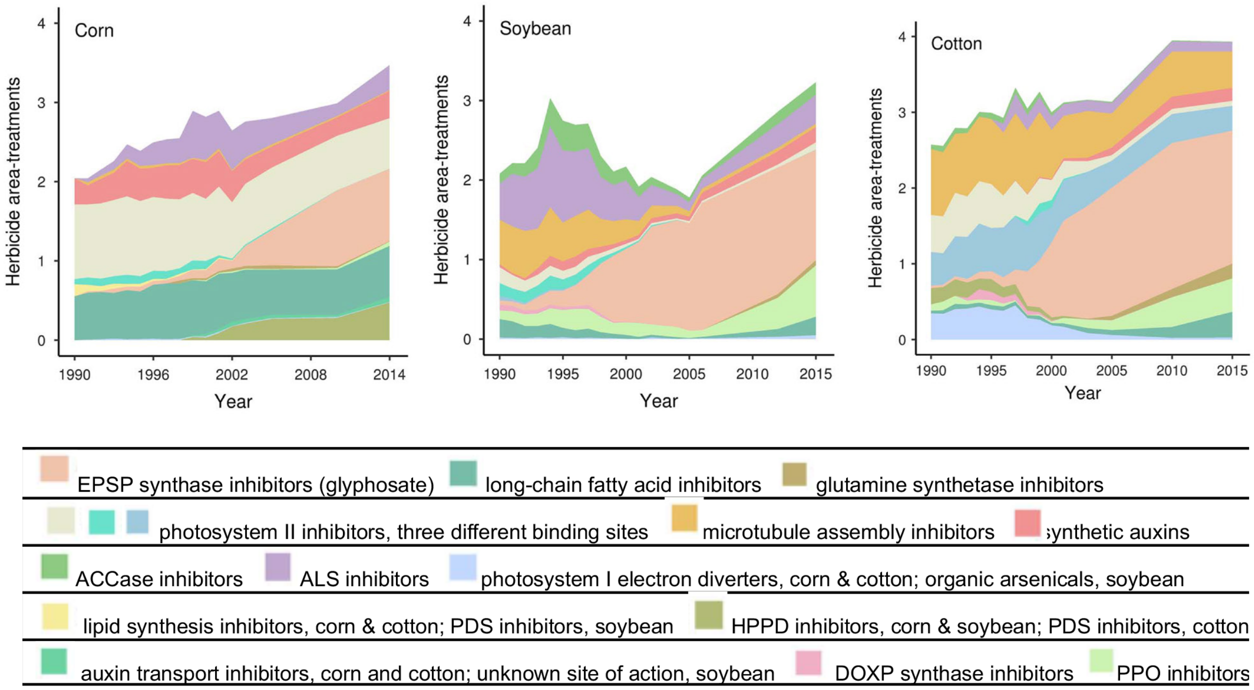
The impacts of GE crops on herbicide use are much more nuanced than their impact on insecticides. As previously discussed, the key is to assess changes in the mix of herbicides by looking at the volumes of each herbicide, weighted by their relative toxicities, applied to a particular crop over time.

Volume Trends

Weed scientist Andrew Kniss begins assessing changes in the mix of herbicides using "area-treatments," rather than lbs.[59] Area-treatments measure the intensity of herbicide application over time by taking the total amount of each herbicide active ingredient applied per crop per year divided by the average application rate (*i.e.*, number of sprays) on that crop within that year, then further divided by the number of planted acres of that crop in that year. For simplicity, think of annual area-treatments as the average number of sprays per acre per year. The graphs in Figure 9 show that the number of area-treatments has increased for all three crops since 1990. These graphs display tradeoffs between different types of pesticides.

As shown in the graphs, for corn, introduction of glyphosate-tolerant crops (*see* Figure 3) coincided with an increase in use of glyphosate and HPPD inhibitors and a decrease in the use of photosystem II inhibitors, such as atrazine. Several other types of herbicides fluctuated or remained relatively constant. For soybean, by 2005 glyphosate had displaced nearly all other herbicides. However, other classes of pesticides such as PPO inhibitors and ALS inhibitors began to make a comeback by the mid-2000s. Cotton saw a decrease in nearly all classes of herbicides other than glyphosate as use of herbicide-tolerant seed became ubiquitous. The decrease was sustained for organic arsenicals, but other herbicides appear to have been supplemented, not replaced. In addition, use of PPO inhibitors and VLCFA inhibitors appears to be increasing in cotton in recent years.

Figure 9. Mix of herbicides used in corn, soybean, and cotton in the U.S., 1990-2015



Source: Kniss (2018)

* Area-treatments measure herbicide application by taking total amount of each herbicide for each yearr, then further divided by the number of planted acres of that crop in that year.

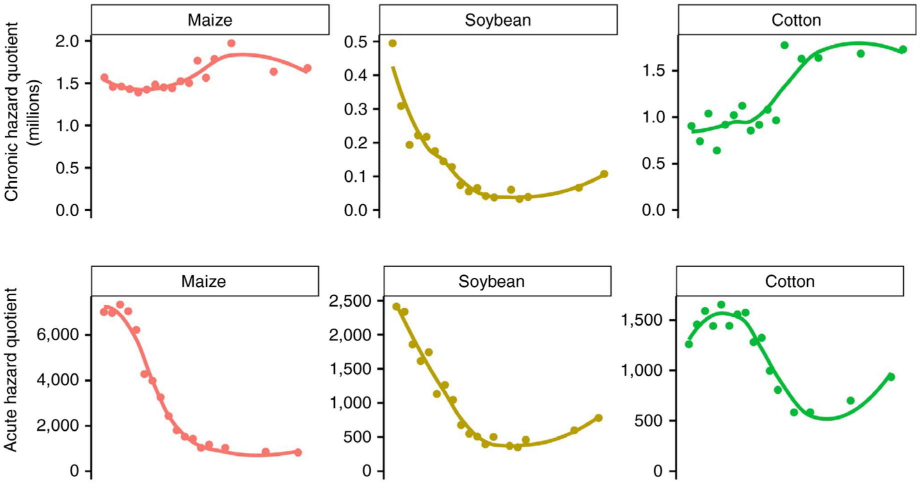
Toxicity Trends

The story becomes yet more complicated with regard to changes in overall toxicity of the mix of herbicides used on each crop. Figure 10 shows the chronic and acute hazard quotients, used to evaluate the relative toxicity of herbicides used in each crop over time, for corn, soybean, and cotton. From 1990 to 2014, there was a 7% increase in chronic toxicity in corn and an 88% decrease in acute toxicity.[60] Cotton experienced similar toxicity trends, with an increase in chronic toxicity and decrease in acute toxicity. In contrast, from 1990 to 2015, both chronic and acute toxicity decreased significantly in soybean—78% and 68%, respectively.[61]

It is difficult to calculate the tradeoffs between increased chronic toxicity and decreased acute toxicity in corn and cotton. However, it is clear that the adoption of GE herbicide-tolerant crops coincided with a dramatic decrease in acute toxicity of herbicides in all three major herbicide-tolerant crops, with persistently lower acute toxicity over the course of the first decade of adoption and beyond.

Overall, while use of glyphosate and total area-treatments have increased with the adoption of glyphosate-tolerant crops, glyphosate seems to have displaced herbicides with higher acute toxicity and, in the case of soybeans, herbicides with higher chronic toxicity as well. If nothing else, these data underscore the need for case-by-case analysis of this complex issue.

Figure 10. Herbicide chronic and acute hazard quotients for maize, soybean, and cotton, 1990-2015



Source: Kniss (2017)

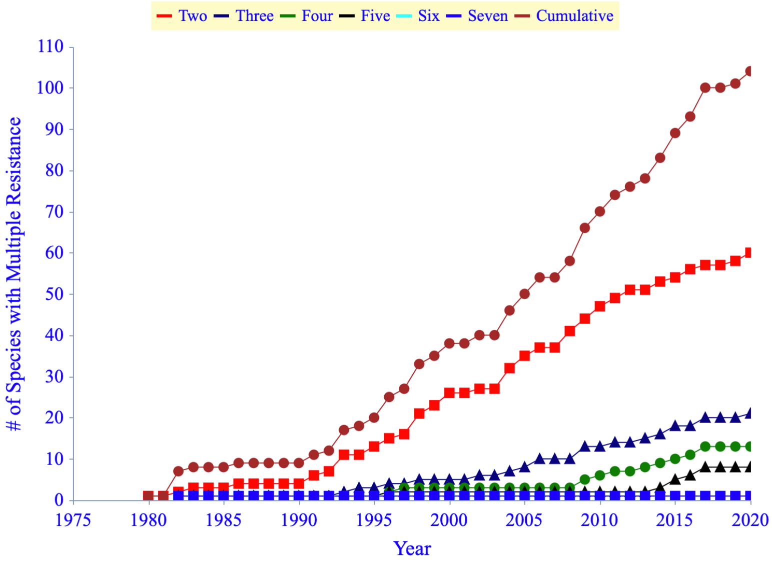
Proceeding with Caution

The fact that the adoption of herbicide-tolerant and insect-resistant GE crop varieties has coincided with decreasing trends in acute herbicide toxicity and overall insecticide use provides an optimistic picture of the impact of these crops on the use of pesticides and their impact on human health and the environment. However, increases in chronic toxicity raise concerns, and there are signs that some beneficial trends have begun to reverse course. Two major threats to the sustainable use of GE crops are herbicide-resistant weeds and *Bt*-resistant pests.

Herbicide Resistant Weeds

Weeds evolve resistance to herbicides used on all crops over time—this is not unique to GE crops. Herbicide-resistant weeds were first reported in the 1950s, decades before the introduction of GE herbicide-tolerant crops.[62] Over time, the evolution of resistance may be inevitable. But just as doctors do not discard life-saving antibiotics because resistance develops, and instead take measures to ensure judicious prescribing practices, farmers can respond to the evolution of herbicide resistance by implementing judicious application practices to prolong the effectiveness of herbicides, while researchers seek to develop new ones.

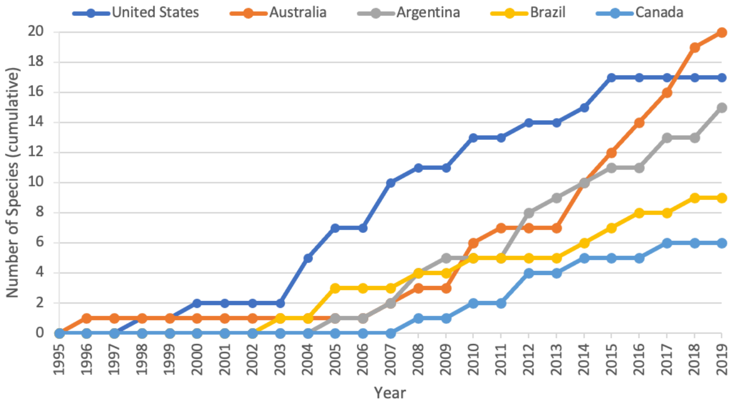
Figure 11. Prevalence of Weeds Resistant to Multiple Herbicides, 1975-2020



Source: Heap (2020)

As of 2015, there were at least 83 reported species of herbicide-resistant weeds in the U.S., many of which are resistant to multiple herbicides and affect multiple crops.[63] Seventy-six of these species have been found in fields planted with wheat, 61 in corn, 51 in rice, and 48 in soybean.[64] Globally, there were at least 104 species of weeds resistant to multiple herbicides as of 2020 (Figure 11).

Figure 12. Prevalence of Weeds Resistant to Glyphosate, 1995-2019



Source: Heap (2020)

However, adoption of GE crops and increased application of glyphosate has been associated with a rapid increase in the prevalence of weeds resistant to glyphosate. By 2015, 17 weed species had evolved resistance to glyphosate in the U.S. (Figure 12) and by 2017, at least one type of glyphosate-resistant weed was found on 120 million acres of U.S. cropland.[65]

Pesticide labeling can be an important tool for promoting responsible use because compliance with labeling requirements is required by law. In January 2020, EPA established new labeling requirements to help farmers reduce the problem of increasing glyphosate resistance in weeds.[66] However, the new label statements merely suggest, not require, best practices for resistance management. The label will now state, "To delay herbicide resistance, take **one or more** of the following steps:…," followed by a list of resistance management techniques including rotating glyphosate with other herbicides, mixing with other less resistance-prone herbicides, adopting integrated weed management programs, scouting for weeds before and after herbicide application, switching to another herbicide if weeds persist after spraying, and reporting instances of suspected resistance.[67,68]

While farmers understand the high cost of having herbicide-resistant weeds in their fields, they face a host of barriers to adopting best practices for herbicide resistance management. Farmer surveys reveal that costs are the most widely-cited barrier.[69,70] Costly changes in individual farmer behavior are needed to protect a collective resource and ultimately avoid even greater costs that result from evolution of resistant weeds. But given the economic tradeoffs and uncertainty faced by individual farmers when implementing resistance prevention practices, EPA would need to explicitly require these practices in order to ensure farmers take a more proactive approach to weed resistance.[71]

Meanwhile, as glyphosate becomes less effective, farmers must consider which herbicides to use in addition to glyphosate, or which herbicides with which to replace it. Depending on which herbicides replace glyphosate, the acute and/or chronic toxicity could significantly increase. The herbicides 2,4-D and dicamba, used on newer varieties of GE herbicide-tolerant crops, each have higher acute and chronic toxicities than glyphosate.[72,73] Some chemicals in the classes of herbicides whose use appears to be on the rise in corn, cotton, and/or soybeans (PPO inhibitors, ALS inhibitors, and VLCFA inhibitors) have higher acute toxicities than glyphosate, few have lower acute toxicities, and most have considerably higher chronic toxicities.[74] Based on current trends, it appears that overall toxicity of herbicides applied to GE crops will increase in the coming years as glyphosate loses its effectiveness.

CSPI has been active in urging EPA to adopt labeling restrictions in order to support farmers in carrying out herbicide-resistance management techniques that would delay the evolution of resistant weeds. In 2014, we asked EPA to strengthen the terms in its proposed registration and label for Enlist Duo, an herbicide containing both glyphosate and 2,4-D, by adding mandatory obligations for crop rotation and limits on the number of sprays per field.[75] In 2016, we pushed for similar requirements as the herbicide dicamba was registered for use on dicamba-tolerant cotton and soybeans, and asked for a limited five-year registration to allow EPA to cancel or amend the registration if dicamba resistant weeds develop.[76] EPA now requires herbicide resistance management statements on the labels of the herbicides used with herbicide-tolerant seeds,[77] but has not taken necessary actions to require crop rotation and spray limits.

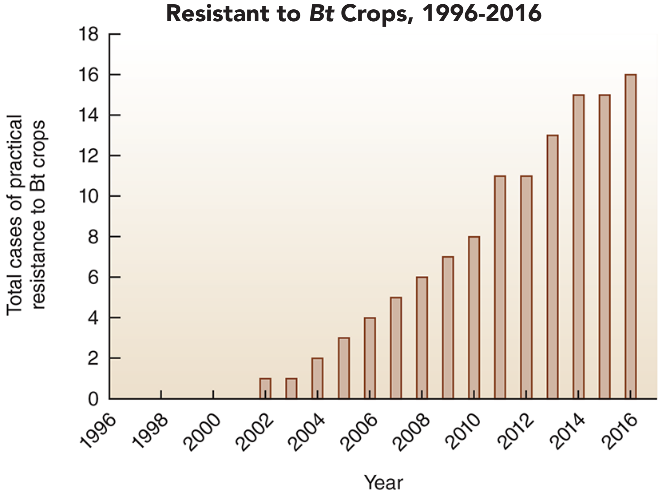
With the recent approval of the herbicide isoxaflutole for use on herbicide-resistant soybeans,[78] and a new petition for deregulation of a GE corn variety with tolerance to five different herbicides,[79] CSPI will continue to advocate for mandatory measures for farmers to slow the development of weed resistance.

Bt Resistant Pests

A potential threat to the effective use of *Bt* crops is the evolution of resistant pests. As of 2016, 16 pest species had developed resistance to *Bt* toxins worldwide (Figure 13), including four species in the U.S. with resistance to 10 different *Bt* toxins.[80]

The increasing number of resistant pests and the areas in which those pests exist is concerning, as farmers will likely turn to more toxic pesticides if pests that are resistant to *Bt* toxins proliferate. However, the resistance management strategy known as the “high dose/refuge” strategy has proven highly effective at delaying the threat of insect resistance (see Box 2).

Figure 13. Global Prevalence of Pests Resistant to *Bt* Crops, 1996-2016



Source: Tabashnik & Carriere (2017)

Unlike with herbicide-tolerant crops, EPA *requires* farmers using *Bt* crops to take actions to prevent resistance by requiring the companies that produce *Bt* seeds to oversee farmers’ implementation of insect resistance management plans.[81] So far, use of the high dose/refuge strategy in the U.S. has prevented the development of any resistant European corn borer populations, therefore all populations of European corn borer in the U.S. remain susceptible to *Bt* products. However, the same is not true for the non-high dose *Bt* varieties that target corn rootworm, where there is documentation of resistant insect populations. One strategy that has been adopted to delay resistance has been to develop *Bt* crops with multiple *Bt* genes (called “stacked” varieties), so that even if a pest develops resistance to one gene, it may be killed by another.[82]

Many *Bt* crops have remained effective against pests for decades. However, concerns remain around lack of compliance with EPA’s refuge requirements for growers of *Bt* crops. Since 2003, CSPI has been advocating for farmers to increase their compliance with EPA’s refuge requirements in order to delay the onset of resistance,[83] and in 2009 CSPI reported that a quarter of *Bt* corn farmers did not comply with their insect resistance management obligations.[84] Surveys of *Bt* corn farmers in North Carolina from 2014 and 2016 showed continued noncompliance, with around one third of farmers stating they did not plan to plant refuges in the upcoming season.[85] Additional efforts from EPA and the seed industry, such as rebates for farmers purchasing non-*Bt* refuge seed, annual on-farm refuge checks, and development of companion refuge hybrids with similar yields as *Bt* varieties, are needed to increase compliance and maintain the efficacy of *Bt* crop technology. In November 2020, CSPI commented on an EPA proposal to improve resistance management for certain pests of *Bt* crops and urged the agency to eliminate the use of single trait (non-stacked) *Bt* corn products; increase refuge requirements and take steps to improve compliance; and require crop and pesticide rotation.[86]

BOX 2. HIGH DOSE/REFUGE STRATEGY

The "high dose/refuge strategy" refers to a combination of steps that GE crop developers and farmers can take to delay the evolution of *Bt*-resistant insects.[87]

"High dose" refers to the amount of *Bt* toxin ingested by an insect that feeds on a *Bt* plant. According to EPA, *Bt* plants must kill 99.99% of insects with which they come into contact in order to be considered "high dose."[88]

"Refuge" typically refers to areas planted with non-*Bt* crops where pests are allowed to thrive, but may also include seed blends (non-*Bt* seed comingled with *Bt* seed and planted in the same field) or natural refuges (adjacent areas with weeds or wild hosts where pests can thrive).[89] The pests found in refuges are not exposed to the *Bt* toxin so they do not develop resistance.

The goal is for the pest population in refuges to be relatively more abundant compared to the few pests that may survive exposure to *Bt* crops and develop resistance. That way, resistant pests are much more likely to mate with pests that have not developed resistance. Since resistance is a recessive trait, when a resistant and non-resistant pest mate, the resistance trait is not carried forward to the next generation of insects in that field.

Looking Forward

Companies continue to isolate additional genes that confer herbicide tolerance and pesticidal properties. They stack these with existing varieties to give farmers more options to control weeds when confronting resistant weeds or resistant pests. Crop varieties stacked with multiple GE traits are the future of GE crop technology. Already, 83 percent of cotton plantings and 79 percent of corn acres were planted with stacked herbicide-tolerant and *Bt* varieties in 2020 (Figure 14).[90] However, new stacked varieties, which have genes that confer resistance to as many as five herbicides, may have greater impacts on herbicide use than their predecessors. As acknowledged by USDA:

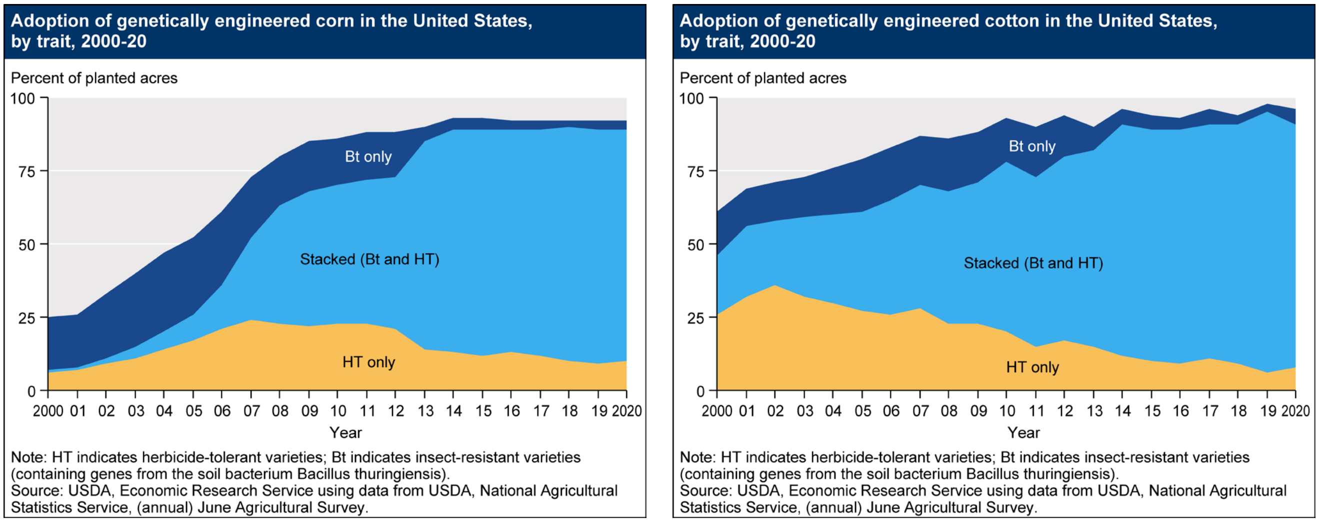
> *"Certain stacked-trait varieties, which are expected to be more common in the future, may increase herbicide use. For example, increased production of stacked-trait soybean resistant to 2,4-D, glufosinate, and glyphosate, or stacked-trait cotton resistant to 2,4-D and glufosinate, could potentially increase overall herbicide use in the United States. For soybean, herbicide programs would combine current rates of glyphosate with additional use of dicamba".*[91]

"Certain stacked-trait varieties, which are expected to be more common in the future, may increase herbicide use"
-USDA APHIS, 2019

As new stacked-trait varieties emerge, we will need to carefully monitor the impact of their adoption on volume and—more importantly—toxicity of herbicides used on these crops.

Meanwhile, farmers should be encouraged to use pesticides judiciously and according to EPA's label requirements. They should implement pest management techniques that do not rely entirely on the use of chemical pesticides, such as crop rotation, soil stewardship to ensure plants get the nutrients they need to recover from damage caused by pests, sanitation measures to eliminate weed seeds and disease vectors, mulching, mowing, hand weeding or mechanical cultivation, providing habitats for beneficial organisms, reducing habitats for pests, and more.[92] Pesticides are one of many tools that help farmers grow our food efficiently, but they come with costs that can be minimized through responsible use and integrated pest management techniques.

Figure 14. Adoption of genetically engineered corn (left) and cotton (right) in the United States, by trait, 2000-2020



Adoption of genetically engineered corn in the United States, by trait, 2000-20

Note: HT indicates herbicide-tolerant varieties; Bt indicates insect-resistant varieties (containing genes from the soil bacterium Bacillus thuringiensis).
Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, (annual) June Agricultural Survey.

Adoption of genetically engineered cotton in the United States, by trait, 2000-20

Note: HT indicates herbicide-tolerant varieties; Bt indicates insect-resistant varieties (containing genes from the soil bacterium Bacillus thuringiensis).
Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, (annual) June Agricultural Survey.

Source: USDA 2020

Take Home Messages

Understanding the impact of GE crops on pesticide use is no easy task. This report is intended to identify the questions that must be addressed when assessing the overall public health impact of these products. Our findings include:

- The impacts of GE crops on pesticide use must be considered on a case-by-case basis: crop by crop and pesticide by pesticide, with particular attention to substitution effects and their implications for the net toxicity of pesticides applied on each crop.
- There is no simple answer to whether the net impact of GE crops on pesticide use has been beneficial or adverse.
- The debate over pesticide use and GE products is not relevant to products with GE traits which are unrelated to pesticide use, such as non-browning apples and potatoes.
- GE insect-resistant crops have been associated with a significant reduction in insecticide sprays across all crops engineered with traits for insect resistance.

- The impact of GE herbicide-tolerant crops upon herbicide use depends on which crop, which trait, and which herbicide(s) one considers.
- Since glyphosate-tolerant crops became widely adopted in the early 1990s, use of glyphosate and overall herbicides has increased in corn, soybean, and cotton (as well as in non-GE crops like wheat and barley).
- But trends in herbicide use are better measured by changes in toxicity than volume, as adoption of herbicide-tolerant crops has changed the mix of herbicides used.
- Acute toxicity of overall herbicide use after the introduction of GE crops decreased for all three major crops (corn, soybean, and cotton) and chronic toxicity of herbicides decreased in soybean by 78%, but increased in corn by 7% and in cotton by 91%.

Crop	**Change in toxicity of herbicide use, 1990-2015**	
	Acute	**Chronic**
Corn	**↓88%**	**↑7%**
Soybean	**↓68%**	**↓78%**
Cotton	**↓65%**	**↑91%**

Source: Kniss 2017

- Weed and insect resistance threaten progress from GE crops.
- Integrated pest management practices must be implemented to mitigate these threats.
- Stacked trait products are increasingly commonplace and represent a potentially promising approach to emerging weed and insect resistance, but could also lead to increased volume and toxicity of pesticide applications.
- The latest herbicide-tolerant crops are designed for use with herbicides that are considerably more toxic than glyphosate. Their adoption and impact on net toxicity of herbicide applications must be closely monitored.
- Updated pesticide use data are needed to assess what is actually happening on U.S. farms today, especially given the increasing adoption of stacked trait varieties and varieties compatible with more toxic herbicides.

Interested in learning more about GE crops and pesticides?

Here are some resources we recommend:

- *Biotech Blog* by Center for Science in the Public Interest https://cspinet.org/topics/biotech-blog
- *Feed Your Mind* website by U.S. Food and Drug Administration https://www.fda.gov/food/consumers/agricultural-biotechnology
- Biotechnology resources from U.S. Department of Agriculture https://www.ers.usda.gov/topics/farm-practices-management/biotechnology/
- Pesticide resources from U.S. Environmental Protection Agency https://www.epa.gov/pesticides
- *A Plant Out of Place* blog by Andrew Kniss https://plantoutofplace.com/author/akniss/
- International Herbicide-Resistant Weed Database http://www.weedscience.org/Home.aspx
- National Academies of Science, Engineering, and Medicine. The Future Role of Pesticides in U.S. Agriculture. *National Academies Press*. 2000. http://dels.nas.edu/Report/Future-Role-Pesticides/9598
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