Friends of the Earth

Rethinking No-Till:

The toxic impact of conventional no-till agriculture on soil, biodiversity, and human health

April 2025

Acknowledgments

This report was written by Sarah Starman, Senior Food & Agriculture Campaigner and Dr. Kendra Klein, Deputy Director of Science at Friends of the Earth, with research support from Dr. Jessica Chiartas at the University of California, Davis.

Friends of the Earth United States, founded by David Brower in 1969, is the U.S. voice of the world's largest federation of grassroots environmental groups, with a presence in 75 countries. Friends of the Earth works to defend the environment and champion a more healthy and just world. We have provided crucial leadership in campaigns resulting in landmark environmental laws, precedent-setting legal victories and groundbreaking reforms of domestic and international regulatory, corporate and financial institution policies.
Visit www.foe.org to learn more.

Report Design: Marie Melvin

Table of Contents

INTRODUCTION

The concept of regenerative agriculture has gained momentum over the past few years, bringing increased interest and funding, from multimillion dollar investments from companies such as Nestle, Mars, and PepsiCo to state and federal funding.[1] With billions of dollars — and the future of our food system — at stake, we must ensure that the practice of regenerative agriculture is robust and is guarded against greenwashing.

"No-till" is widely considered a regenerative practice, and tillage is often called out as universally detrimental to the health of the soil. Reduced tillage, including no-till, is the practice most often included in definitions and descriptions of regenerative agriculture given by nonprofit organizations, extension agencies, and farmers.[2] No-till is one of the practices that has been incentivized through state and federal funding and major companies such as Tyson Foods, ADM, Cargill, and Bayer are promoting or funding no-till as a regenerative practice.[3, 4, 5, a]

This report compiles the latest scientific research and U.S. Department of Agriculture (USDA) data on the leading no-till crops in the U.S. by acreage — corn and soy. No-till and minimum-till corn and soy account for approximately 28% of the nation's total cropland, or 107 million acres.[6,7,8,b] The majority

---

[a] For Ground by Bayer. Bayer Carbon Program. Bayer AG: Leverkusen, Germany. Webpage. Accessed January 7, 2025. https://bayerforground.com/carbon-initiative

[b] For corn and soy, the USDA reports data on "no-till or minimum-till" acreage combined in their Chemical Use Survey Highlights. We used this data as the basis of our analysis. We refer to these acres as "no-till" throughout this report for simplicity and to follow the term of art that has shaped the public conversation and billions worth of public and private spending. It is also worthwhile to note that "no-till" is largely misnomer: USDA data show that at least 80% of "no-till" corn, soybean, wheat, and cotton acres were tilled at some point over a four-year period. (Claassen, R., Bowman, M., McFadden, J., Smith, D., Wallander, S. 2018. Tillage Intensity and Conservation Cropping in the United States. U.S. Department of Agriculture: Washington, D.C. September, https://mssoy.org/sites/default/files/documents/tillage-study-ers-sep-2018-six.pdf.

of this corn and soy is not produced as food for human consumption, but for livestock feed and biofuels.[c,d]

What is regenerative agriculture?

The definition of regenerative agriculture is open to debate. Like the term sustainable, some definitions are robust while others are weak or even meaningless. Regenerative agriculture has been broadly described as a holistic farming approach that challenges the status quo of conventional agriculture and its degenerative impacts on the environment and human health. Robust approaches prioritize protection of soil health and biodiversity to achieve resilience, water conservation, and carbon sequestration. Meaningful approaches include reduction or elimination of synthetic pesticides and fertilizers as a central tenet and result in improved ecological, social, economic, and human health outcomes, including long-term food security.

In this report, we examine the production of conventional no-till corn and soy against the stated goals of regenerative agriculture — sequestering soil carbon, improving air and water quality, bolstering farmers' resilience to climate change, and protecting biodiversity and human well-being — and find that it falls woefully short.

To be clear, no-till in and of itself does not have inherently negative impacts. When incorporated into a holistic, ecological approach to farm management, no-till can lead to positive outcomes including reduced erosion. It is when no-till is implemented as a standalone practice in large-scale, chemical-intensive systems that it not only falls short of regeneration, but results in negative externalities.

Large-scale, chemical-intensive agriculture currently predominates in the U.S., not through the fault of farmers, but because that is what public policies and markets support. The adoption of no-till by conventional growers who once practiced standard tillage is indicative of the fact that many farmers are interested in conservation and are willing to adapt and implement new practices. We must now restructure our policies and markets to support these and other farmers to achieve truly regenerative agriculture.

In this report, we show that **conventional no-till is soaked in toxic pesticides and synthetic fertilizers.**

We find that **the vast majority (93%) of U.S. corn and soy acreage grown in no-till and minimum-till management systems relies on toxic pesticides that harm soil health and threaten human health**. That represents an area approximately the size of California.

While reducing tillage can reduce mechanical disturbance to the soil, the soil in most conventional no-till systems is far from "undisturbed." Rather than relying on physical cultivation to manage weeds and/or terminate cover crops, conventional no-till often relies on increased use of chemical herbicides that damage the soil organisms at the heart of regenerative agriculture. A strong body of science shows that synthetic pesticides — a term that encompasses herbicides, insecticides, and fungicides — disrupt the soil microbiome and harm soil organisms that are central to the goals of regenerative agriculture: building healthy soil, sequestering carbon, protecting biodiversity, conserving

[c] More than 80% of U.S. corn goes to the production of feed and ethanol fuel. USDA Economic Research Service. Feed Grains Sector at a Glance. U.S. Department of Agriculture: Washington, D.C. Webpage. Accessed January 7, 2025. https://www.ers.usda.gov/topics/crops/corn-and-other-feed-grains/feed-grains-sector-at-a-glance/

[d] More than 90% of U.S. soy that is not exported is crushed, creating soybean meal – used in livestock feed – and soybean oil, approximately half of which goes to biofuel production. Vaiknoras, K., Hubbs, T. 2023. Characteristics and Trends of U.S. Soybean Production Practices, Costs, and Returns Since 2002. USDA Economic Research Service: Washington, D.C. June. https://www.ers.usda.gov/webdocs/publications/106621/err-316.pdf?v=2345.2

water, improving farmers' climate resilience, and protecting human health.[9,10] 86% of regenerative practitioners agree that a target outcome of regenerative agriculture is to build soil health[11] — yet this is difficult, if not impossible, to achieve while broadcasting toxic pesticides and overapplying synthetic fertilizers.

Conventional no-till is soaked in toxic pesticides that harm soil life and human health. A staggering one-third of the U.S.'s total annual pesticide use can be attributed to corn and soy grown in no-till systems.

We find that **a staggering one-third of the U.S.'s total annual pesticide use can be attributed solely to corn and soy grown in no-till systems.** Alongside devastating impacts to soil health, these chemicals are energy-intensive to produce, resulting in a major greenhouse gas footprint, and they are also associated with significant harm to wildlife and to human health. Children are the most vulnerable to the impacts of pesticide exposure, and farmers, farmworkers, and rural communities are on the frontlines.

We also show that **at least 90% of no-till corn and soy acres (91% of soy and 88% of corn) rely on genetically engineered seeds,** driving a cycle of increased pesticide use, and that **potentially all no-till corn seeds are coated with neonicotinoids,** a class of insecticides harmful to soil life, pollinators, other beneficial organisms, and to human health, the most concerning of which are banned in the European Union.

We summarize **current scientific data that show no clear relationship between no-till and soil carbon sequestration.** This belies the widely held assumption that no-till is definitively linked to increased soil carbon sequestration. We place particular emphasis on this point, as both public and private initiatives to promote regenerative agriculture — with millions of dollars at stake — are currently operating on this faulty assumption. For example, the USDA listed no-till as a climate-smart agricultural practice that will "increase soil organic matter"[12] and chemical company Bayer is paying farmers up to $6 an acre for practicing standalone no-till because of its alleged ability to enhance soil carbon sequestration.[13]

Finally, we summarize data showing that tillage is not universally detrimental to soil health and that **tillage can be part of regenerative agriculture.** Research shows that the impact of tillage on the soil depends greatly on the depth, spatial coverage, and frequency of tillage and the implement used, as well as other practices in the farming system. For example, the literature shows that some diversified organic farms achieve regenerative outcomes, such as substantial improvements in soil organic matter and other soil health metrics, while using tillage in combination with practices such as cover cropping, compost application, and diverse crop rotations. Our findings illustrate why **a narrow focus on tillage is insufficient and misleading when trying to determine whether or not a farm or system is regenerative.**

No-till is a misnomer

It is important to understand that "no-till" is largely a misnomer. U.S. Department of Agriculture (USDA) data show that at least 80% of "no-till" corn, soybean, wheat, and cotton acres were tilled at some point over a four-year period. However, we use "no-till" throughout this report to follow the term of art that has shaped the public conversation and billions worth of public and private spending. Our findings are based on USDA reporting on "no till or minimum till" acreage.

Classifying conventional no-till as "regenerative" invites extensive greenwashing. A narrow focus on tillage is insufficient and misleading when trying to determine whether a farm is regenerative.

This report serves as an alarm bell warning that classifying conventional no-till as "regenerative" invites extensive greenwashing from major food and chemical companies. Pesticide companies like Bayer and Syngenta have capitalized on the growing interest in soil health by promoting conventional no-till — which relies heavily on their pesticides, genetically engineered seeds, and digital agriculture platforms — as regenerative.[14,15,16] In fact, the pesticide industry is deeply intertwined with the ascendance of no-till over the past few decades, as discussed in this report.

Given the urgency of the public health, biodiversity, and climate crises we face, the growing interest in regenerative agriculture must be harnessed in service of robust approaches that truly increase soil health and carbon sequestration, improve air and water quality, bolster farmers' resilience to climate change, and protect biodiversity and human well-being. **Truly regenerative agriculture cannot be boiled down to single practices, such as no-till — it requires holistic, systems-based approaches.** And truly regenerative agriculture must be a force to reduce the use of harmful pesticides and synthetic fertilizers. Regenerative agriculture definitions, certifications, and initiatives must explicitly center and prioritize agrochemical reduction if they are going to meet their stated goals.

Companies, policymakers, and regenerative advocates should promote, uplift, and incentivize systems-based approaches that are rooted in shifting away from a toxic, industrial model of agriculture towards diversified and ecological cropping systems. They should provide financial, technical, and other forms of support to conventional growers to adopt practices and systems that build fertility and manage pests with significantly fewer, if any synthetic chemical inputs. Reducing inputs in conventional systems is possible, and it comes with a host of benefits for the climate, biodiversity, and human health – and along with regenerating soils and ecosystems, it can lower costs and improve farm profitability.

Equally, companies, policymakers, and advocates must do a better job investing in and supporting growers who are already practicing diversified organic and other leading forms of regenerative agriculture. As we discuss below, decades of scientific data show that on average, diversified organic growing systems sequester more carbon, build healthier soils, increase biodiversity, and improve resilience — thereby protecting farmers' yield during droughts and floods — compared to conventional growing systems. Investing in low-input, systems-based approaches like diversified organic agriculture is a no-regrets solution for achieving the goals of regenerative agriculture.

II. KEY FINDINGS

We found that:

Conventional no-till has a toxic footprint

- At least 93% of no-till and minimum-till corn and soy acreage in the U.S. uses synthetic herbicides. That represents an area the size of California — approximately 100 million acres of U.S. cropland.
- Herbicide use in no-till corn and soy can be associated with a whopping 33% of total annual pesticide use in the U.S. — 285 million out of 851 million pounds of pesticides (a term that encompasses herbicides, insecticides, and fungicides). These chemicals are associated with significant harm to human health, biodiversity, and soil health, including the soil invertebrates and microorganisms that are the basis of truly regenerative agriculture.
- We estimate that the majority of use (61%) is herbicides classified as highly hazardous to human health and/or the environment — 173 million out of 285 million pounds of herbicides used annually in no-till corn and soy.
    - Glyphosate (aka Roundup), dicamba, 2,4-D, atrazine, acetochlor, and S-metolachlor[e] account for the majority of herbicide use in corn and soy. Of these, glyphosate, 2,4-D, and acetochlor are classified as highly hazardous.
    - Glyphosate alone accounts for an estimated 40% of the total use of herbicides in no-till corn and soy. The glyphosate used in no-till corn and soy account for approximately 13% of the total use of pesticides in U.S. agriculture annually.
    - The use of the highly hazardous herbicide paraquat has also increased dramatically in soy production in the past decade.
- Conventional no-till is associated with increased herbicide use over standard tillage. This is due to greater reliance on chemical forms of weed management compared to conventional systems with tillage. Based on our conservative estimates, at least 26 million pounds of additional herbicides are used annually due to conventional no-till management in corn and soy.
- At least 89% of conventional no-till corn and soy acres (91% of soy and 88% of corn) rely on seeds genetically engineered (GE) to be herbicide tolerant. These GE seeds are associated with a dramatic increase in use of glyphosate and growing use of antiquated, hazardous herbicides dicamba and 2,4-D.
- Neonicotinoid seed coatings are used on up to 100% of conventional no-till corn acreage. This represents up to 2.47 million pounds of toxic insecticide used annually. Neonicotinoids are associated with significant harm to soil life, pollinators, and human health.

Conventional no-till has a significant carbon footprint

- The herbicides and synthetic fertilizers used in conventional no-till have a significant carbon footprint. The energy-intensive production of herbicides associated with no-till corn and soy results in upwards of 3.4 million metric tons of CO_2-equivalent emissions annually based on available estimates. The production, transportation, and application of nitrogen

---

[e] We have aggregated use of S-metolachlor and metolachlor for our findings because they are functionally very similar chemicals. See Appendices 1 and 2 for the breakdown between S-metolachlor and metolachlor use in corn and soy. For more information about the two chemicals, see: Benbrook, C. M. 2001. Factors Shaping Trends in Corn Herbicide Use: An Update and Technical Report. Northwest Science and Environmental Policy Center: Sandpoint, Idaho. July

fertilizer used on no-till corn acres likely accounts for between 18.4 million to 49.3 million metric tons of CO_2-equivalent emissions. At the high end, these emissions are equivalent to 11.4 million cars on the road for a year — approximately the number of cars in the top 9 no-till states: Kansas, Nebraska, South Dakota, North Dakota, Montana, Iowa, Illinois, Missouri, and Indiana.

Conventional no-till does not increase soil carbon sequestration

- The latest science shows that, on average, conventional no-till production does not increase soil carbon and in some cases has been found to reduce it.

Tillage can be part of regenerative farming systems

- Tillage is not universally detrimental to soil health. Research shows that the impact of tillage on the soil depends greatly on the depth, spatial coverage, and frequency of tillage and the implement used, as well as other practices in the farming system. A narrow focus on tillage is insufficient and misleading when trying to determine whether or not a farm or system is regenerative.

Truly regenerative agriculture is systems-based

- Truly regenerative agriculture cannot be boiled down to single practices, such as no-till — it requires holistic, systems-based approaches.
- Reducing synthetic pesticide and fertilizer use in conventional agriculture, using systems-based approaches to build fertility and manage weeds and pests, has clear benefits for the climate, soil, and biodiversity — and can be achieved without harming yield or profitability.
- Agroecological farming, including diversified organic production, is a no-regrets solution for achieving soil health, promoting biodiversity, and mitigating and adapting to climate change. Research also shows that it can produce abundant food for a growing world population.[17]

III. THE RISE OF NO-TILL

Tillage — mechanically turning or mixing soil in order to prepare it for cultivation — is a longstanding agricultural practice. A wooden plow, one of the earliest instruments of tillage, was likely invented and first used in ancient Mesopotamia more than 5,000 years ago.[18] Tillage became commonplace in modern, industrial agriculture with the invention of the tractor and implements such as the moldboard plow, disc harrow, and rotary tiller. The moldboard plow was widely adopted in the U.S. starting in the 19th century, and for decades stood as the most common tillage implement in American agriculture.[19] Moldboard plowing is an intensive form of tillage that inverts the soil to a depth of 8 to 12 inches, causing significant disturbance to soil structure at a great depth and typically leaving less than 15% of the soil surface protected and covered.[20] Intensive tillage with moldboard plows, combined with drought, led to the Dust Bowl in the 1930s, drawing national attention to the role that agricultural practices play in supporting — or undermining — soil health.[21]

As evident in the devastation of the Dust Bowl, intensive or excessive tillage followed by extended periods of bare fallow can leave soil vulnerable to wind and rain and result in a variety of negative impacts, including increased soil loss (or erosion), soil compaction, harm to soil invertebrates (such as earthworms), loss of soil organic matter, and diminished capacity to hold water and nutrients.[22] Soil erosion is of particular concern. The U.S. is predicted to lose 3 inches (300 years' worth) of soil by 2100, threatening sustainable crop production and farmland fertility.[23] Concerns about the connection between intensive tillage and soil erosion have led farmers to explore alternative practices over the past few decades, including conservation tillage, reduced tillage, strip-till, and no-till. All of these systems — some of which are overlapping categories — seek to prevent erosion and minimize other negative impacts by reducing the frequency or intensity of tillage and leaving crop residues on the field to cover and protect the soil.

No-till, in particular, has risen in popularity over the past few decades. The use of no-till has increased in corn, wheat, soy, and cotton since 2001, including more than doubling on corn and wheat acres.[24] The Natural Resource Conservation Service (NRCS) estimates that no-till is now practiced on 33% of the nation's total cultivated cropland.[25] Although a small number of organic producers have adopted no-till as a practice, the majority of no-till adoption (by acreage) has occurred in the conventional production of row crops, such

as corn and soy. Like conventional row crop production with tillage, conventional no-till is most often implemented as part of industrial systems that depend on the use of toxic pesticides and synthetic fertilizers.

Chemical companies are deeply intertwined with no-till's ascendance. When the concept of industrial no-till first emerged in the 1970s, companies such as Imperial Chemical Industries (the first company to commercialize the highly hazardous herbicide paraquat) saw an opportunity to expand the market for their chemicals. They conducted no-till experiments and helped spread the concept, explicitly marketing pesticides as a replacement for tillage.[26,27] "Let paraquat be your plow," reads a 1972 advertisement placed by Chevron in the magazine No-Till Farmer.[28] The increased efficacy of herbicides in the 1990s and the rise of 'Roundup Ready' corn and soy genetically engineered to withstand herbicide applications also enabled an ongoing shift towards no-till in the past few decades.[29,30,31]

A 1972 ad from No-Till Farmer for paraquat that says "Let Paraquat be your plow." (Photo from No-Till Farmer/Civil Eats)

In recent years, pesticide companies have capitalized on the nation's growing interest in soil health by making regenerative claims about conventional no-till, which relies heavily on their chemicals, genetically engineered seeds, and digital agriculture platforms.[32] Pesticide companies like Bayer and Syngenta are claiming that industrial, chemical-intensive no-till production is regenerative and climate-smart[33,34,35] — despite the large carbon footprint associated with their chemicals and the grave threat they pose to soil, human, and planetary health.

Two problematic assumptions have proliferated alongside the rise of no-till and the attempt to classify conventional no-till as "regenerative." The first problematic assumption is that no-till is definitively linked to soil carbon sequestration and soil health. The second is that tillage is universally detrimental to the health of the soil. Our findings reveal significant flaws in both of these assumptions and illustrate why a narrow focus on tillage alone is insufficient when trying to determine whether or not a farm or system is "regenerative."

The reality is that tillage is nuanced. Tillage can be detrimental to soil health — contributing to soil loss, compaction, and other harms, as discussed above — but this isn't always the case. Tillage can also be used responsibly and in some soils may be necessary to break up compaction and allow for healthy root and plant growth. For example, numerous studies have documented that diversified organic farms increase soil organic matter and improve other soil health metrics while still using full tillage,[36,37] and sometimes even more frequent tillage than conventional standard tillage systems.[38,39] No-till, when combined with other practices, can also be part of regenerative growing systems, and in some contexts can demonstrably reduce erosion, improve soil health outcomes, and achieve other benefits. On the other hand, chemical-intensive no-till — which encompasses the majority of no-till acreage — is not definitively linked to carbon sequestration and is accompanied by a toxic footprint, climate costs, and threats to human health that are far from the true meaning of "regenerative."

IV. TOXIC FOOTPRINT

A. Toxic herbicides are the foundation of most conventional no-till

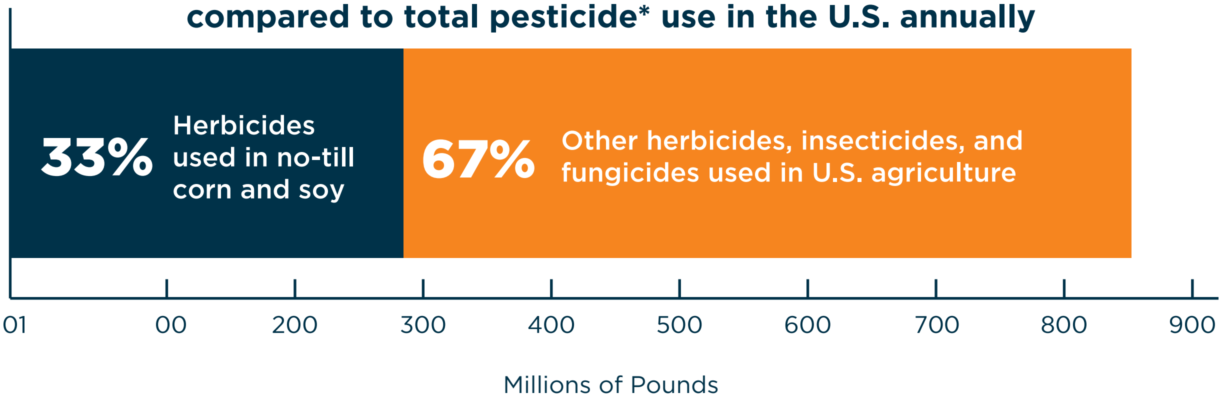
While conventional no-till systems reduce tillage, that doesn't mean the soil in these systems is "undisturbed," something often touted both as a principle of regenerative agriculture and a benefit of no-till. **Conventional no-till trades mechanical disturbance for chemical disturbance**. The herbicides used in conventional no-till to manage weeds and/or terminate cover crops are associated with significant damage to soil organisms, which are the drivers of 80-90% of soil processes, such as nutrient cycling and carbon sequestration.[40] These organisms are the heart of regenerative agriculture, as detailed below in Part V, Section 3.

Our analysis found that at least 93.2% of no-till corn acreage and 93.5% of no-till soy acreage in the U.S. uses herbicides (see Appendix 6: Methodology). That represents approximately 100 million acres of cropland, an area roughly equal to the state of California.[41,42] This is a conservative estimate, as we assumed that the minimum possible percent of conventional no-till corn and soy acres rely on herbicides.

In total, we estimate that 285 million pounds of herbicides are used on no-till corn and soy acres each year. To put this in perspective, **the herbicides used in no-till corn and soy production account for a whopping 33% of total annual pesticide use in U.S. agriculture** (see Figure 1)**.**

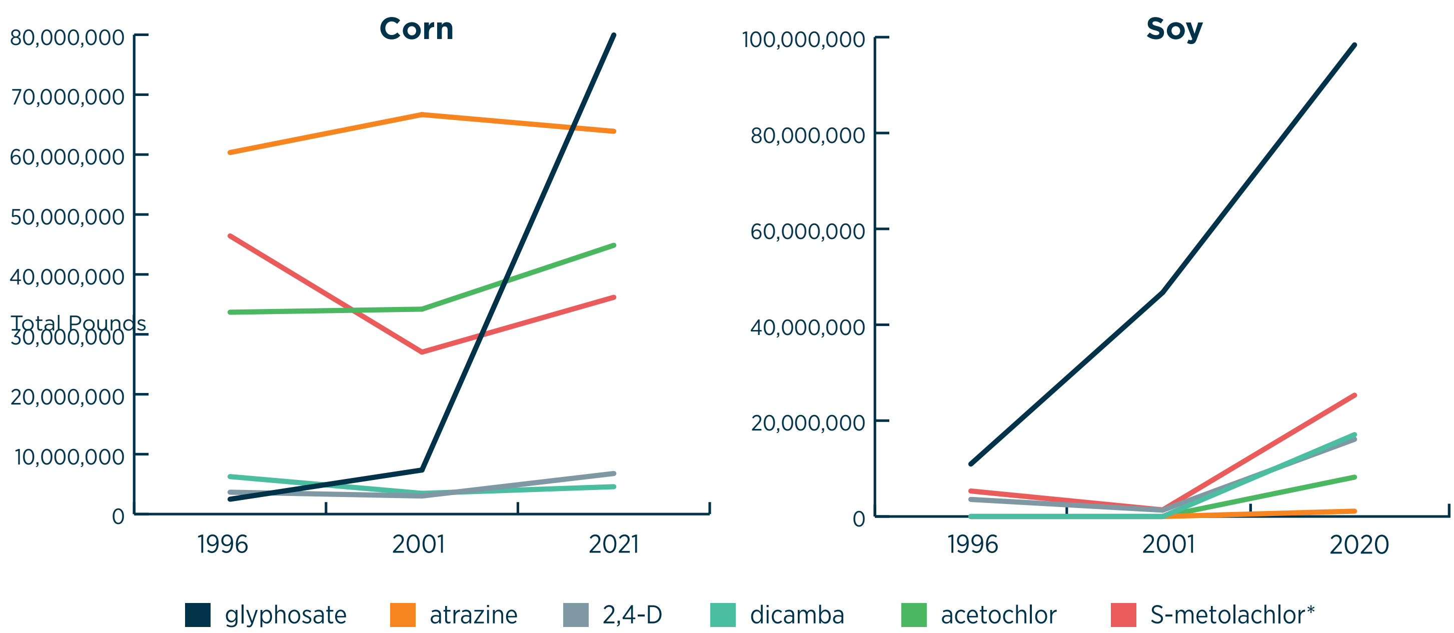
These chemicals are associated with significant harm to the environment and human health. Glyphosate, dicamba, 2,4-D, atrazine, acetochlor, and S-metolachlor are currently the most widely used herbicides in corn and soy production. (See Appendix 1 and 2 for a full list of herbicides, insecticides, and fungicides used in corn and soy production.) Use of these six herbicides in corn and soy has dramatically increased in the past decade (see Figure 2). Three of these chemicals are classified as highly hazardous: glyphosate, 2,4-D, and acetochlor. Glyphosate is far and away the most heavily used. **We estimate that 112 million pounds of glyphosate are used annually on no-till corn and soy.** Glyphosate alone accounts for an estimated 40% of the total use of herbicides in no-till corn and soy. The glyphosate used in no-till corn and soy account for approximately 13% of the total use of pesticides in U.S. agriculture annually.

Figure 1: Herbicides used in conventional no-till corn and soy compared to total pesticide* use in the U.S. annually



Results generated using Pesticide Use Data System (PUDS) based on USDA QuikStat surveys and NASS data for corn and soy. 2021 is the most recent year of surveyed data for pesticide use in corn, 2020 for soy.
* The term 'pesticide' encompasses herbicides, insecticides, and fungicides.

Figure 2: Top 6 herbicides used in U.S. corn and soy in 2020/2021: Change in use over time



Results generated using Pesticide Use Data System (PUDS) based on USDA QuikStat surveys and NASS data for corn and soy. 2021 is the most recent year of surveyed data for pesticide use in corn, 2020 for soy.
*Represents the aggregate amount of S-metolachlor and metolachlor.

B. Conventional no-till is associated with increased herbicide use over standard tillage

Without the ability to control weeds through tillage, no-till growers must find alternative approaches. Diversified organic or biodynamic growers who implement no-till are prohibited from using synthetic herbicides, relying instead on cultural practices like crop rotation or cover crops to minimize weed pressure, and/or the integration of practices like grazing animals, hand weeding, or occultation. Conventional growers typically replace tillage with herbicide use for weed management.[43,44] This can result in increased use of herbicides over standard tillage. Scholars have observed 10% - 41% increases in herbicide use with the adoption of no-till in conventional systems.[45,46] To be conservative, we used the lower end of this range (10%) to estimate that approximately **25,911,600 additional pounds of herbicides are used annually in the U.S. as a result of conventional no-till management of corn and soy.**

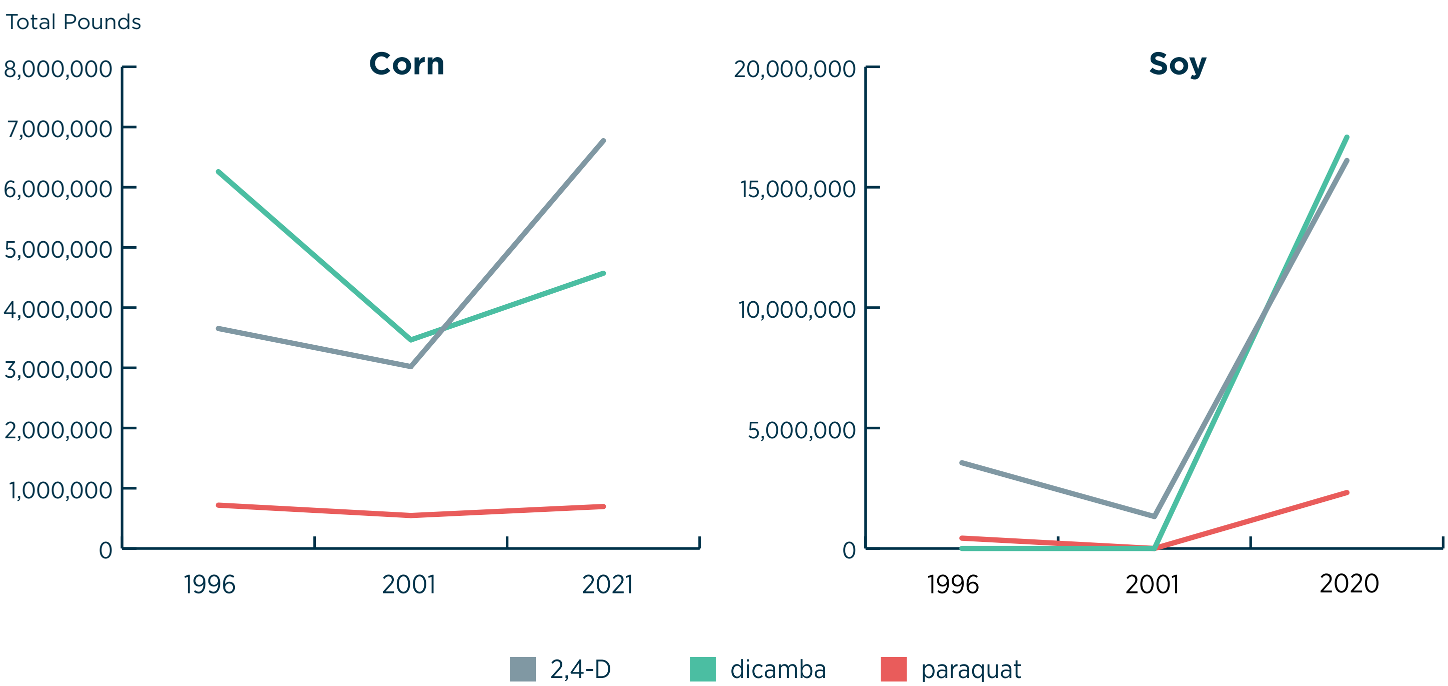
Some of the increase in herbicide use may be a result of residue retention — the practice of leaving crop or cover crop residues on the field. The U.S. Natural Resource Conservation Service (NRCS) Conservation Practice Standard requires residue retention (with a minimum of 60% residue cover on the soil throughout the year) for a farm to qualify as "no-till."[47] Residue retention can be beneficial for reducing soil erosion, buffering soil temperatures, and preserving soil moisture. However, conventional growers practicing residue retention may increase the amount — both the rate and frequency — of herbicide application because the residues can absorb a significant amount of herbicide, requiring more to be sprayed to ensure contact with the soil where it is most effective.[48,49,50] As most of these herbicides are highly water soluble, the portion that is absorbed in the residue can also run off and end up downstream after rain or irrigation events. The contamination of waterways with toxic herbicides threatens ecosystems as well as access to safe drinking water and safe recreation.

C. Conventional no-till is associated with increasing use of antiquated, hazardous chemicals

Glyphosate — aka Roundup — is by far the most widely used herbicide in conventional corn and soy production.[51] However, the use of other herbicides is rapidly increasing as the efficacy of glyphosate wanes. We found that the use of 2,4-D and dicamba has doubled in corn and increased 25-fold in soy in the past two decades.[52] These are antiquated chemicals that are more toxic to human health than glyphosate, according to U.S. Environmental Protection Agency (EPA) assessments of toxicity.[f] They are also associated with serious harm to the environment, as discussed at length in Part IV, Section F, below. The use of paraquat, a highly acutely toxic herbicide linked to increased risk of Parkinson's disease and other serious health problems, has also increased 5-fold in soy production in the past two decades.[53,54]

A dramatic increase in glyphosate was driven by the advent of 'Roundup Ready' corn and soy varieties, which were genetically engineered by Monsanto in the 1990s to withstand the spraying of glyphosate. Since then, the use of glyphosate has increased 32-fold on corn and 9-fold on soy (see Figure 2).[55] This ubiquitous use of glyphosate resulted in the proliferation of glyphosate-resistant "superweeds." Superweeds now plague over 100 million acres of U.S. farmland[56] and cost farmers an estimated $10 billion annually[57] — equivalent to about 5% of the total GDP generated by U.S. farms each year.[58] Pesticide companies have capitalized on this by genetically engineering crops to withstand a broader suite of herbicides, including 2,4-D, dicamba, and glufosinate, and marketing them as a way to combat superweeds that no longer respond to glyphosate. The latest genetically engineered corn and soy seeds are designed to resist two herbicides, and seeds with resistance to as many as four are available.[59]

Figure 3: Increases in 2,4-D, dicamba, and paraquat use in U.S. corn and soy



Results generated using Pesticide Use Data System (PUDS) based on USDA QuikStat survey. 2021 is the most recent year of surveyed data for pesticide use in corn, 2020 for soy.

[f] The EPA has set the chronic reference dose (cRfd), a measure of chronic toxicity, at .01 mg/kg/day for 2,4-D; .03 mg/kg/day for dicamba; and .1 mg/kig/day for glyphosate. A higher cRfd indicates that the EPA has judged the chemical is less chronically toxic. U.S. EPA IRIS System. IRIS Home: Advanced Search. U.S. Environmental Protection Agency: Washington, D.C. Web database. Accessed January 9, 2025. https://iris.epa.gov/AdvancedSearch/

Most conventional no-till farmers use genetically engineered seeds. Our analysis shows that, at a minimum, **89% of no-till corn and soy acres are planted with crops genetically engineered to withstand glyphosate and other toxic herbicides** (91% of soy and 88% of corn; see Appendix 6: Methodology).[60]

Genetically engineered herbicide-tolerant varieties drive the cycle of increased herbicide use, decreased efficacy, and increased incidence of superweeds, yet the pesticide industry is doubling down on this failed approach. Conventional no-till production, like conventional production with standard tillage, is contributing to this ramp-up in herbicide use, causing negative externalities and undermining our ability to achieve truly regenerative outcomes.

D. Herbicides used in conventional no-till harm human health

According to USDA data, at least 15 herbicides classified as highly hazardous to human health or the environment are used in conventional corn and soy production in the U.S.[61,62] We estimate that **173 million pounds of highly hazardous herbicides may be attributed to no-till corn and soy annually**.

Regenerative agricultural systems should not only regenerate soil and ecosystem health, but human health as well. Yet decades of data show that the pesticides widely used in conventional agriculture can disrupt and derail the healthy functioning of our bodies. Children and infants in utero are the most physiologically vulnerable to the effects of exposure, and farmers, farmworkers, and rural communities are on the frontlines of exposure.[63,64]

Figure 4 provides an overview of the health harms associated with the top six herbicides used in U.S. corn and soy production (see Appendix 5 for supporting research). Note that the three herbicides classified as highly hazardous — glyphosate, 2,4-D, and acetochlor — as well as the other three, are associated with a range of human health impacts, including cancers, reproductive and developmental toxicity, endocrine disruption, and more.

It is misleading to call agricultural systems that depend heavily on use of these and other toxic chemicals "regenerative." Regenerative farming systems should sustain and improve human health, not threaten it.

Figure 4: Summary of human health impacts linked to top herbicides used in U.S. corn and soy

	Glyphosate	Dicamba	2,4-D	Atrazine	Acetochlor	S-Metolachlor*
Cancer	X	X	X	X	X	X
Genotoxicity	X	X	X			
Reproductive Toxicity	X	X	X	X	X	X
Developmental / Birth Defects	X	X	X	X		X
Neurotoxicity		X	X	X	X	
Liver / Kidney Impacts	X	X	X		X	X
GI System / Gut Microbiome Impacts	X				X	
Endocrine Disruption	X		X	X	X	X
Irritant / Sensitizer	X	X			X	X
Other	X*		X**	X***		

Data is from studies on both S-metolachlor and metolachlor
*Associated with metabolic syndrome
**Associated with retinal degeneration and cataracts
***Associated with cardiac effects and immunotoxicity
See Appendix 5 for more information

E. Herbicides used in conventional no-till harm the environment

Along with human health harms, the six herbicides most commonly used in conventional corn and soy production also harm biodiversity above and belowground, from birds and fish to essential soil organisms. This damage threatens the stability of our farming systems, which depend on the complex array of ecosystem services that biodiversity provides. A healthy and intact web of life is fundamental to feeding ourselves and future generations.

Figure 5 provides an overview of the risks posed by the six herbicides to different classes of organisms (see Appendix 6 for supporting research). Given that these chemicals are herbicides — designed to kill plants — it should come as no surprise that they pose risks to native plant communities. Dicamba is particularly problematic in this regard as a volatile chemical that is prone to drift. Dicamba can cause injury to crops and wildlife thousands of feet from where it is applied, threatening native plant communities and the insects and birds that depend on those plants for their food and shelter.[65]

Many of these herbicides also pose risks to essential pollinators like bees. The EPA notes that there are concerns for bees related to the use of dicamba and acetochlor,[66,67] and glyphosate has been found to negatively impact bees' reproduction, broods, foraging and navigation abilities, learning, and memory.[68] Pollinators like bees are responsible for one in three bites of food that we eat.[69]

When these toxic herbicides run off into waterways, they can also cause injury and death to fish, aquatic organisms, and amphibians; and finally, many of these herbicides pose risks to birds and mammals. Atrazine is worth highlighting, as the Refined

Ecological Risk Assessment for Atrazine, published by the EPA in 2016, demonstrates just how ecologically damaging this herbicide is. The EPA found that the risks posed by atrazine to birds, mammals, and fish exceed the EPA's level of concern for chronic exposure by as much as 22, 168, and 62 times, respectively.[70]

For more details on how the herbicides used in conventional no-till harm soil organisms, see Part V, Section C below.

Figure 5: Summary of ecological risks posed by top herbicides in U.S. corn and soy

Risks posed to:	Glyphosate	Dicamba	2,4-D	Atrazine	Acetochlor	S-Metolachlor*
Native Plants	X	X	X	X	X	X
Pollinators	X	X	X	X	X	X
Birds	X	X	X	X	X	X
Fish/Aquatic Organisms	X	X	X	X	X	X
Mammals	X	X	X	X	X	
Amphibians	X	X		X		
Soil Organisms	X		X		X	

* Data is from studies on both S-metolachlor and metolachlor

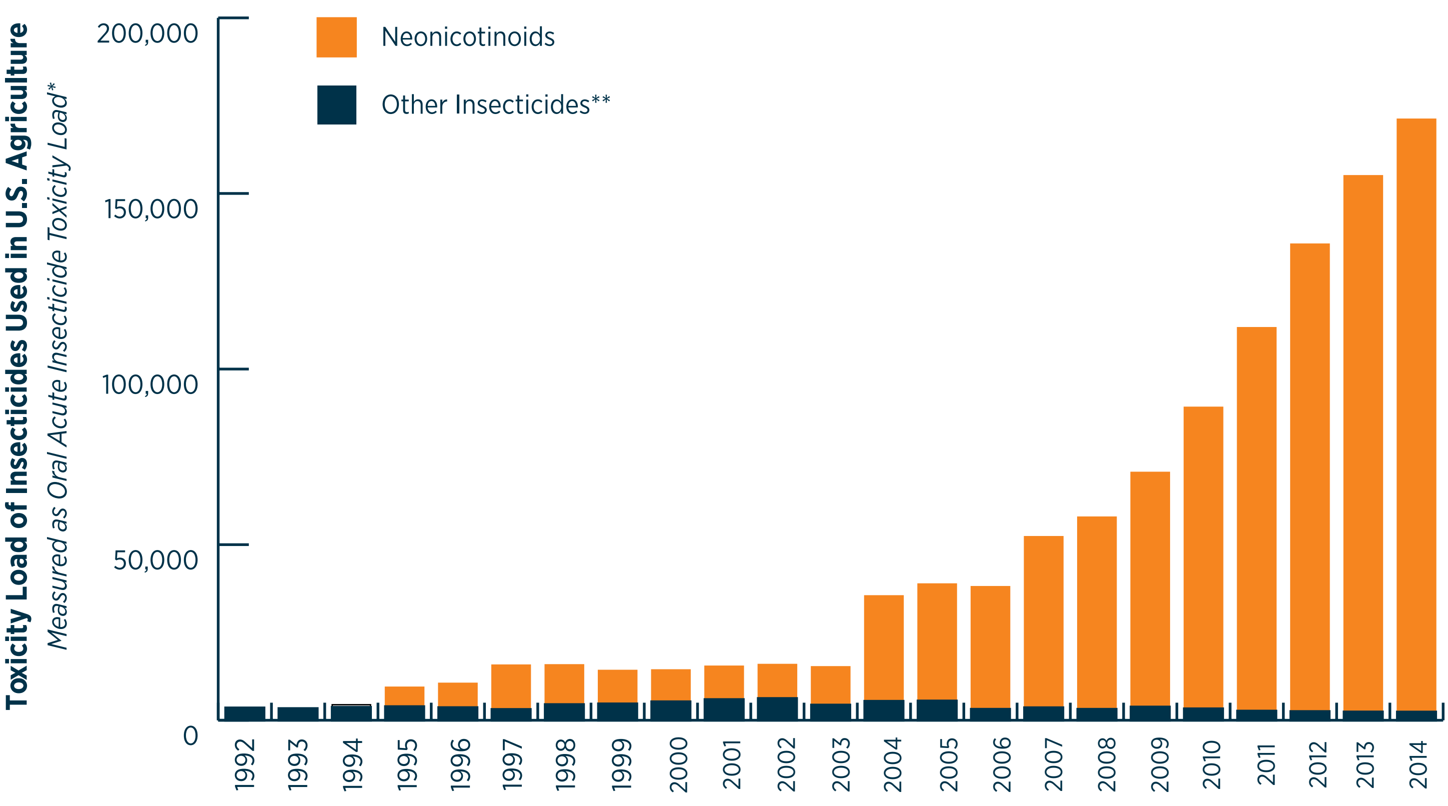
See Appendix 6 for more information.

F. Conventional no-till uses neonicotinoids associated with devastating harm to ecosystems and human health

Researchers estimate that between 79% and 100% of corn grown in the U.S. relies on the use of neonicotinoid insecticides as seed coatings.[71] **This means that seed coatings in no-till corn may account for up to 2.47 million pounds of neonicotinoid (or neonics) use annually.**[72] The available data did not allow us to calculate the percentage of no-till soy that likely uses neonic-coated seeds; however, the data indicate that at least 40% of conventional soy in the U.S. is grown with neonic-coated seeds.[73]

Neonics are a class of insecticides associated with devastating ecological harm. They are one of the main drivers of insect declines worldwide, including the massive loss of pollinators, and are responsible for serious harm to soil and aquatic ecosystems.[74,75] U.S. agriculture has become nearly 48 times more toxic to insect life since the introduction of neonics in the 1990s.[76] They are also a key factor driving mass loss of birds,[77] and the EPA asserts that continued use will likely push more than 200 threatened and endangered species toward extinction.[78]

Figure 6: Increase in Toxicity of U.S. Agriculture for Insects



*For method, see DiBartolomeis and Kegley et al., 2019. An assessment of acute insecticides toxicity loading of chemical pesticides used on agricultural land in the United States, PLOS One.
** pyrethroids, organophosphates, pyrazoles, spinosyn, N-methyl carbamates, others

Neonics are "systemic," so when applied at the root of plants or as seed coatings, they are absorbed and permeate the entire plant as it grows, poisoning its nectar, pollen, and fruit. Neonics are also far more persistent in the environment than other insecticides and can kill insects for months to years after application. They travel in soil and water, spreading threats well beyond the original application site.

The largest use of neonics in the U.S. is as coatings on corn and soy seeds. Neonic seed coatings result in a tremendous cost to biodiversity but provide little to no yield or economic benefits to farmers, on average,[79,80] and in some cases may even decrease yield by killing pollinators and pest predators (i.e. "good bugs").[81,82] Yet they are widely used because a near-monopoly in the seed industry held by pesticide corporations leaves farmers with few other options.[83]

Neons also threaten human health. They have been associated with adverse developmental and neurological outcomes, including memory loss and tremors and congenital heart defects and neural tube defects.[84] Some neonics have also been linked to reproductive toxicity and endocrine disruption.[85,86,87]

G. Synthetic fertilizers used in conventional no-till harm human health and the environment

The use of synthetic fertilizers is ubiquitous in conventional corn production, including in no-till systems. At least 92% of no-till corn acres in the U.S. can be associated with application of synthetic nitrogen at an estimated average application rate of 150 pounds per acre.[88] **That represents 50.44 million acres and a total use of 7.6 billion pounds of synthetic nitrogen on conventional no-till corn.**

The widespread use of synthetic nitrogen fertilizer in agriculture threatens biodiversity and human health. When excess nitrogen runs off of fields and contaminates surface waters, it can lead to catastrophic "dead zones" — areas that lack oxygen, making it impossible for aquatic wildlife to survive. The Gulf of Mexico, the Chesapeake Bay, the Great Lakes, and other critical marine and freshwater ecosystems in the U.S. are negatively impacted by dead zones every year.[89] Fertilizer use is also a major source of nitrate pollution in drinking water, and exposure to nitrates in drinking water has been linked to cancer, thyroid disease, and neural tube defects, among other health issues.[90] Synthetic fertilizers can also harm soil life, as discussed in Part V, Section C below.

Since soybeans are legumes that can naturally fix nitrogen in the soil, they are associated with far lower applications of synthetic fertilizer (537 million pounds annually versus 12.3 billion pounds annually for corn).[91] While USDA data shows that 30% of soybean acres received applications of nitrogen fertilizer, it was not possible for us to determine the percent of conventional no-till soy that nitrogen fertilizer was applied to.

V. CLIMATE COSTS

The past few years have seen a surge of interest in agricultural practices that can reduce greenhouse gas emissions and/or draw down carbon from the atmosphere. Despite widely held assumptions, scientific evidence shows that investing in conventional no-till will not help us reach ambitious climate goals.

Research shows that no-till is verifiably linked to a reduction of direct fossil fuel emissions on-farm, typically attributed to the need for fewer tractor passes.[92,93,94] However, this may be offset by additional passes associated with increased application of herbicides. Other factors in conventional no-till systems also undermine the impact of this reduction in fuel use. First and foremost, conventional no-till corn and soy production are soaked in fossil fuels in the form of synthetic fertilizers and pesticides. The production and use of these chemicals is linked to significant greenhouse gas emissions. Second, there is little to no scientific evidence supporting the assumption that no-till increases soil carbon sequestration. Third, the pesticides commonly used in conventional no-till have been shown to harm soil organisms, undermining the ability of soils to sequester carbon, cycle nutrients, and maintain a healthy structure.[95,96] Healthy soil structure is essential for farmers' resilience to climate change and extreme weather events.

A. Fossil fuel-based pesticides and fertilizers used in conventional no-till have a significant carbon footprint

99% of all synthetic chemicals, which includes pesticides and fertilizers, are derived from fossil fuels.[97] Fossil fuels are also used as an energy source during the manufacturing process of these chemicals.[98]

We estimate that eliminating synthetic pesticides and fertilizers in conventional no-till corn production could mitigate as much or more CO_2-equivalent emissions per acre as the adoption of cover crops, under some conditions. Meta-reviews estimate that cover crop adoption could mitigate approximately .4 - .83 metric tons of CO_2-equivalent emissions per acre, per year.[99,100,101] In comparison, we estimate that eliminating synthetic fertilizer and herbicides in conventional no-till corn could avert approximately .39 - 1.02 metric tons of CO_2-equivalent emissions per acre per year. (See Appendix 4: Methodology). Yet while cover crops are a large part of USDA's 2024 list of 'climate-smart' practices, agrochemical reduction is mostly ignored. There is no practice standard related to reducing or eliminating synthetic pesticide use on the list at all.[102] To transform our agricultural system into one that regenerates and mitigates climate change, the carbon footprint of pesticides and synthetic fertilizers must be addressed, and

Eliminating synthetic pesticides and fertilizers could be as good for the climate as cover cropping per acre of corn

Scientists estimate that cover crop adoption could mitigate approximately **.6 metric tons of CO2-equivalent emissions per acre, per year.**

Estimates range from .4 - .83 CO2-e

We estimate that eliminating synthetic fertilizer and herbicides in conventional no-till corn could mitigate approximately **.7 metric tons of CO2-equivalent emissions per acre, per year.**

Estimates range from .39 -1.01 CO2-e

agrochemical reduction must be prioritized alongside other effective practices.

1. Pesticides

Publicly available data on the carbon cost of pesticide production is limited and out-of-date, in large part due to commercial confidentiality held by chemical companies. While it would be useful to have specific calculations for individual chemicals, the available research only provides broad assessments of different types of pesticides. Available data estimate that insecticide production generates between 15 and 19 kilograms (kg) of CO_2-equivalent emissions per kg of insecticide while herbicide production results in between 18 and 27 kg of CO_2-equivalent emissions per kg of herbicide on average — more than double the amount of emissions from burning a gallon of gasoline.[g,103] (This calculation is from a study at Cranfield University prepared for the agrochemical industry.) Using these data, we found that **the production of herbicides associated with no-till corn and soy may result in upwards of 3.4 million metric tons of CO_2 equivalent emissions annually** (see Appendix 4: Methodology). This is the equivalent of around 760,000 cars on the road for a year.[104]

Researchers have calculated the energy use associated with the production of some specific pesticides, including glyphosate. The production of glyphosate was found to result in 31.29 kg of CO_2-equivalent emissions for every kg of the pesticide.[105] This translates to approximately 1.6 million metric tons of CO_2-equivalent emissions annually that can be attributed to the glyphosate used in no-till corn and soy production in the U.S.

2. Fertilizers

Synthetic nitrogen fertilizer is associated with significant emissions along its entire supply chain, from production to transportation to application. It is energy-intensive to manufacture, with the production of each

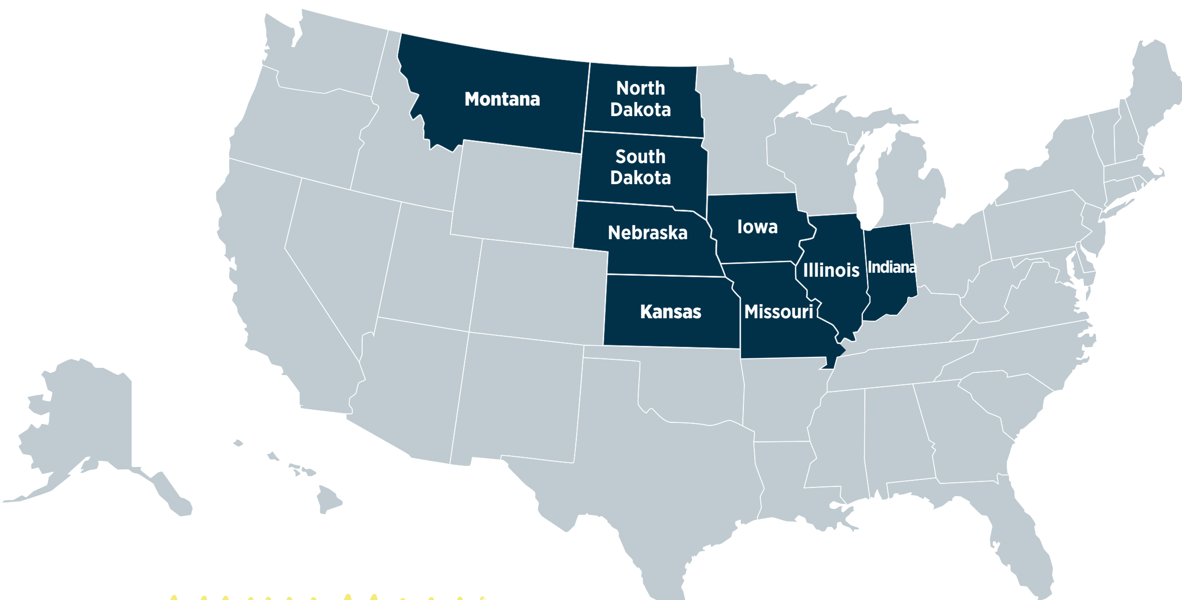
[g] In this section of the report, we use the metric system (kilograms and metric tons) because greenhouse gas emissions are typically expressed as metric tons of CO_2-equivalent.

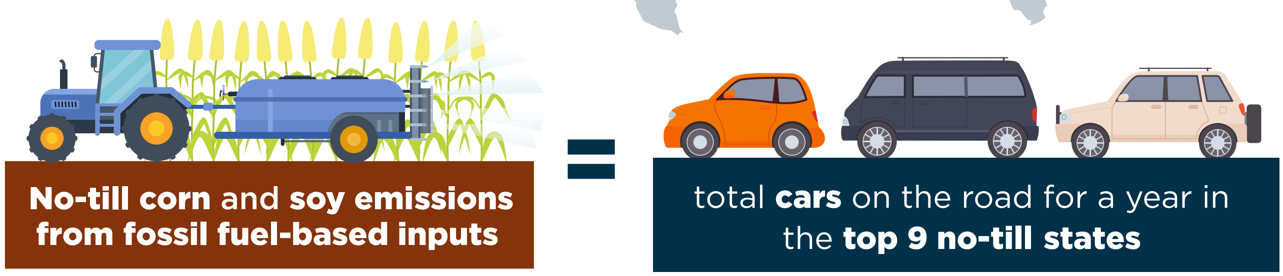
metric ton resulting in an estimated 3.1 - 4 metric tons of CO_2-equivalent emissions.[106] It also results in significant nitrous oxide (N_2O) emissions when from it is applied. N_2O is a potent greenhouse gas with a global warming potential 273 times when greater than that of carbon dioxide.[107] The N_2O from agricultural soils is the single largest source of direct greenhouse gas emissions from U.S. agriculture, according to the U.S. EPA.[108]

We estimate that the nitrogen fertilizer used on no-till corn acres likely accounts for between 18.4 million to 49.3 million metric tons of CO_2-equivalent emissions annually. At the high end, that's the equivalent of about 10.7 million cars on the road for a year.[109]

Combining our analysis of the emissions associated with the herbicides used in no-till corn and soy and our analysis of the nitrogen fertilizer used in no-till corn, we estimate a total carbon footprint of 21.9 million to 52.8 million metric tons of CO_2-equivalent emissions per year. This means that **eliminating the use of synthetic herbicides and fertilizer in no-till corn would avert an estimated .39 - 1.02 metric tons of CO_2-equivalent emissions per acre, per year.**

This may be conservative. Other scholars have estimated that replacing synthetic fertilizer in conventional systems (for example, with organic amendments and farming practices that stimulate biological activity and replenish nitrogen in the soil) may be able to mitigate roughly 1.7 metric tons of CO_2-equivalent emissions per acre, per year.[110] We also assumed that the least possible percentage of no-till corn acres uses fertilizer, and that these acres applied fertilizer at the average rate for conventional corn.





The combined emissions associated with synthetic fertilizer and pesticide production use in no-till corn and soy production can be associated with the equivalent CO2 emissions of up to 11.4 million cars on the road for a year — approximately the number of cars in the top 9 no-till states.

Calculated using the U.S. Department of Agriculture 2022 Census of Agriculture, U.S. Department of Transportation State Motor Vehicle Registrations – 2020, and U.S. EPA Greenhouse Gas Emissions from a Typical Passenger Vehicle

B. No-till is not proven to increase soil carbon stocks

Soil carbon sequestration is often touted as a benefit of no-till, but this isn't scientifically accurate. Recent research shows that much of the data that led to this erroneous assumption suffers from a common error: not measuring deeply enough in the soil profile. Shallow sampling (20 - 30 cm) is likely to overestimate the carbon storage benefits of no-till; as tillage distributes soil deeper in the soil profile, while no-till stratifies it in the surface.[111] When the entire zone of soil influenced by tillage is considered, the positive benefits of no-till on soil carbon disappear.[112]

Multiple meta-reviews looking deeper at the soil profile — beyond 30 cm — have found that while no-till is linked to increased carbon in the surface layers of the soil, it is also linked to lower concentrations at deeper depths, meaning there is no overall change in carbon stocks.[113,114,115] In other meta-reviews, no-till has been found to actually reduce overall soil carbon stocks.[116]

The fact that no-till concentrate soil carbon in shallower layers — rather than increase overall stocks — is problematic, as most no-till farmers till intermittently. USDA data show that at least 80% of "no-till" corn, soybean, wheat, and cotton acres were tilled at some point over a four-year period.[117] This intermittent tillage can result in an immediate loss of substantial amounts of carbon from shallow layers of the soil.[118,119] Thus, the lack of redistribution of carbon within the soil profile associated with no-till may actually undermine deeper, more stable soil carbon storage.

No-till may sequester soil carbon under some conditions, but it depends on site-specific context and the overall farm system. One meta-review found that when no-till was combined with double-cropping, it did sequester a significant amount of carbon.[120] However, this study still found that, on the whole, there was no relationship between no-till and increased carbon storage.

What's more, research shows that, in some climates, no-till may lead to an increase in N_2O emissions from the soil compared to standard tillage[121122]. Again, N_2O is a potent greenhouse gas with a global warming potential 273 times greater than that of carbon dioxide.

The bottom line is that it is not scientifically sound to assume that no-till, as a standalone practice, will result in increased soil carbon storage.

C. Agrochemicals used in no-till are a serious threat to the organisms that underpin soil carbon sequestration and farmers' resilience

The pesticides and synthetic fertilizers used in conventional no-till systems are associated with significant harm to soil health. These chemicals threaten critical soil organisms, disrupt microbial activity, undermine soil carbon sequestration, and alter soil ecosystems.

Two meta-reviews show that pesticide use is incompatible with healthy soil ecosystems. One focuses on soil invertebrates, including earthworms, ants, beetles, mites, springtails, nematodes, and ground nesting bees. It found that commonly used classes of pesticides kill or harm soil invertebrates in 71% of cases evaluated.[123] Another looked at microorganisms like bacteria and fungi. It found that field doses of pesticides can reduce soil microbial activity (32-40%) and biomass (15-48%) and alter microbial community structure (54-90%).[124] **Multiple studies suggest that the routine use of pesticides has greater and more disruptive effects on soil bacterial and fungal communities than routine tillage does.**[125,126] And pesticides have been specifically linked to negative impacts on nitrogen-fixing bacteria — undermining the ability to build fertility in the soil through biological activity.[127]

Although the effects of glyphosate — the most widely used pesticide in corn and soy production — on soil are not fully understood, mounting evidence shows cause for concern.[128,129,130] Studies have found that glyphosate damages the ecology of mycorrhizal fungi that enable the flow of carbon to the soil.[131,132,133] Earthworms are also at risk from glyphosate exposure. One study found that the casting activity of earthworms at the soil surface nearly disappeared after three weeks of glyphosate application and that reproduction of earthworms dropped by half after three months.[134] Other potential negative effects of glyphosate on soil health include an increase in pathogenic microorganisms in the soil, impairment of respiration of soil-dwelling organisms, and nutrient immobilization for plants and microorganisms.[135]

Research also shows that use of synthetic fertilizers can hinder, alter, and impair biodiversity and biological activity in the soil, which can lead to a decline in soil organic matter and degradation of soil structure.[136,137]

Soil carbon sequestration depends on the very soil organisms that agrochemicals harm and kill. Soil carbon sequestration takes place as plants breathe in carbon from the air through photosynthesis. Some of this CO_2 is converted into organic compounds that make up the plant biomass and the rest is exuded into the soil through the plants' roots, feeding an ecosystem of microorganisms. Invertebrates also feed on fallen plants, breaking them down and excreting carbon-rich casts and feces and mixing organic materials into the soil as they go. By harming soil microorganisms and invertebrates, the agrochemicals used in conventional no-till undermine the ability of the soil to sequester carbon.

Soil biodiversity also plays a central role in water conservation and improving farmers' resilience. Invertebrates like earthworms and springtails are ecosystem engineers, crafting and maintaining the structure of soil. Healthy soil with good structure acts as a sponge — readily absorbing water during intense rains and holding on to it during dry times — improving farmers' outcomes during weather extremes.[138,139] Thus, the agrochemicals used in conventional no-till also undermine farmers' resilience to the impacts of droughts and floods, which will continue to worsen with climate change.

VI. SOLUTIONS

Leveraging the momentum behind regenerative agriculture to create transformative change in our food system is central to responding to the intertwined crises of biodiversity loss and climate change while addressing the massive threats to public health posed by the dominant industrial food system.

Interest in regenerative agriculture has exploded in the past decade, and, as stated above, the fact that many conventional growers who once practiced standard tillage have adopted no-till systems is an indication of an interest in conservation and a willingness to adapt and implement new practices. Government agencies, corporations, and others interested in regenerative agriculture must harness this interest and provide financial, technical, and other forms of support to conventional growers to assist their transition to truly regenerative agriculture. And equally, we must support growers who are already practicing diversified organic and other leading forms of regenerative agriculture. We must lift up systems-based approaches to growing food that research shows have broad benefits for the soil, human health, and the climate.

A. Reducing fertilizer and pesticide use in conventional systems is possible and beneficial

Within conventional agricultural production, reducing the use of synthetic pesticides and fertilizers is a critical way to shift toward more regenerative systems.

Research shows that reducing use of pesticides in conventional systems is possible. There are a variety of practices that conventional growers can use to manage weeds and pests without chemical inputs, particularly when those practices are combined in holistic, systems-based approaches. For example, when implemented robustly, Integrated Pest Management (IPM) — a pest management strategy that prioritizes long-term prevention, least-toxic approaches, and minimizing risks to people and the environment — is one approach that can reduce chemical use and improve outcomes in conventional systems. One study found that IPM was able to reduce insecticide use in corn and watermelon cropping systems by 95% over four years while yields were maintained or increased.[140] Another study evaluated data from 85 IPM projects across Asia and Africa and found that, on average, yields increased and pesticide use declined by 30%.[141]

Synthetic fertilizer reductions are also possible. At a minimum, conventional growers can implement improved nutrient management: applying fertilizer from the right source at the right rate, right time, and right placement (sometimes referred to as the "4R" framework). If multiple 4R principles are implemented in conjunction, it can decrease excess fertilizer use and improve the efficiency of nutrient uptake by crops.[142] Scholars who have modeled the potential impact of improved nutrient management estimate that, if adopted on 27% of eligible acres globally by 2050, it could mitigate over 2 billion metric tons of CO_2-equivalent emissions and save farmers around $23 billion.[143] Given the tremendous greenhouse gas emissions and severe water pollution associated with nitrogen fertilizers, however, our long-term goal should be supporting conventional growers' to build fertility through holistic sets of practices (cover cropping, crop rotations, using organic soil amendments, etc.) that ultimately eliminate the need for synthetic fertilizers entirely. While increased efficiency is a practical first step, it is imperative that we begin working on a time-bound transition away from synthetic fertilizers and towards truly regenerative agriculture that derives fertility from healthy, biologically active, well-managed soils.

Reducing synthetic inputs is not only possible, it can save farmers money on costs and even increase profitability. For corn farmers, for example, fertilizer alone typically accounts for approximately 15-25% of total production expenses,[144] and U.S. farmers spend approximately $19 billion on pesticides annually.[145] One study found that farming systems that employed regenerative practices including eliminating insecticide use, planting multispecies cover crops, and reducing tillage were up to 78% more profitable than more chemical-intensive conventional farm systems.[146] A long-term program to reduce pesticide use by implementing IPM in Texas cotton led to an average increase in net returns of $43 per acre for producers.[147] And a study of 946 conventional farms in France found that lower pesticide use was not associated with reduced productivity or profitability.[148]

It's also clear that protecting and fostering biodiversity by reducing the use of harmful pesticides can benefit farmers. A meta-review found that an abundance and diversity of insects in agricultural systems can improve productivity and yield outcomes.[149] As noted in Section V, Part 3, a diversity and abundance of soil organisms supports essential nutrient cycling and healthy soil structure, which improves farmers' resilience to extreme weather events. Healthy ecosystems provide a variety of important services to farmers, and reducing pesticide use maintains these ecosystems and sustains the key benefits they provide.

Public and private initiatives must support conventional growers to prioritize input reduction as they move along the pathway of regeneration. Reducing the use of agrochemicals in conventional agriculture is a no-regrets solution that has the potential to benefit biodiversity, the climate, soil health, human health, and farm profitability and yield.

B. Decades of research show the climate, biodiversity, and health benefits of organic

At the same time as we invest in reducing agrochemical inputs in conventional systems, public and private actors must also invest in expanding organic systems. Diversified organic is a leading form of climate-smart and regenerative agriculture, as demonstrated by decades of peer-reviewed research.[150] Organic agriculture has been consistently proven to lead to positive outcomes for the climate. On average, organic farms use less energy, emit fewer greenhouse gasses, and improve soil carbon sequestration compared to conventional farms.[151,152,153] Long-term trials conducted by the USDA found that organic farms can sequester, on average, 400-600 more pounds of carbon per acre than conventional farms, including conventional no-till farms.[154,155]

Organic also offers broad soil health benefits beyond carbon sequestration. For example, a long-term trial at the University of Minnesota found that soils under organic management demonstrated: higher microbial biomass and activity; improved storage of plant nutrients (such as phosphorus and potassium); and reductions in soil-borne diseases compared to soils under conventional management.[156] Organic fields have also been found to have 30–50% greater soil aggregation and ten times higher water infiltration than conventional fields. The fact that organic fields can take up and hold more water allows them to be more resilient to extreme weather events — intensifying due to climate change — including drought and floods.[157,158]

By not using synthetic pesticides, organic farms also protect essential biodiversity. On average, organic farms host 50% more living organisms than conventional farms.[159,160] The increased populations of beneficial insects, birds, mammals, reptiles, and soil organisms on organic farms maintain the web of life and ensure that we can feed ourselves and future generations.[161] Additionally, organic farming protects people — farmers, farmworkers, rural communities, consumers — from the health impacts of these toxic pesticides, safeguarding human health and wellbeing.[162]

Investing in diversified organic agriculture is another no-regrets solution that will help us achieve the important goals of regenerative agriculture.

C. Tillage can be part of regenerative farming systems

It is critical to recognize that, when implemented in the right ways, tillage can be part of truly regenerative farming systems. Farms in Korea, China, and Japan have retained healthy soils and remained productive even after being tilled for more than 3,000 years.[163] It is true that excessive tillage can lead to a variety of negative impacts on the soil, including soil erosion, as discussed earlier in this report.[164] But tillage is not a monolith. The impact of tillage on the soil depends greatly on the depth, spatial coverage, and frequency of tillage and the implement used, as well as other practices in the farming system. When it comes to soil carbon sequestration, for example, studies have shown that practices such as crop diversity have a greater impact on the level of carbon in the soil than tillage does.[165]

Much evidence that tillage can be part of regenerative farming systems comes from research conducted on organic systems. Organic farmers are legally required to "select and implement tillage and cultivation practices that maintain or improve the physical, chemical, and biological condition of soil and minimize soil erosion."[166] Numerous studies have documented that diversified organic farms using practices such as cover cropping, compost application, and diverse crop rotations achieve substantial improvements in soil organic matter and other soil health metrics while still using full tillage[167,168] and sometimes even more frequent tillage than conventional standard tillage systems.[169,170] Some organic systems with tillage have also demonstrated reduced soil erosion compared to conventional systems, because they had improved soil structure that prevented erosion.[171] We highlight this research to demonstrate that tilling — on organic farms or otherwise — can be part of regenerative farming systems, depending on context.

VII. RECOMMENDATIONS

A. Make agrochemical reduction a central pillar of regenerative agriculture

The evidence presented in this report makes clear that the reduction of agrochemicals must be a central pillar of regenerative agriculture. This is not currently the case. In a 2020 study of regenerative practitioners (nonprofit organizations, extension agencies, and farmers), only 30% cited "using no or low external inputs" as a key practice, and only 18% and 23% cited "using no synthetic pesticides" and "using no synthetic fertilizers" as key practices, respectively.[172] Yet 86% agree that a target outcome of regenerative agriculture is to build soil health — a goal that is difficult, if not impossible, to achieve while broadcasting toxic pesticides and overapplying synthetic fertilizers.

Regenerative definitions, initiatives, and labeling programs that do not address the need for input reduction leave the door open for greenwashing and fail to confront the way that agrochemicals drive catastrophic biodiversity loss, harm soil organisms, and threaten human health. Unfortunately, many emerging regenerative labeling programs for farms and the products they sell have failed to adequately address input reduction. If regenerative agriculture initiatives are going to meet their stated goals, they must explicitly center and prioritize a transition away from toxic pesticides and synthetic fertilizers.

B. Invest in research on reducing tillage without the use of toxic agrochemicals

Because reduced tillage and no-till are beneficial in some contexts – particularly for reducing erosion – a growing number of researchers and farmers are experimenting with techniques, such as roller-crimping, flame weeding, occultation, and animal grazing that may be able to replace herbicides to effectively suppress weeds in no- and minimum-till systems.[173,174,175] Holistic management systems that combine no-till with other beneficial practices have the potential to improve soil health, climate, and biodiversity outcomes, and may even lower input costs for farmers.[176] More federal research dollars are needed to: (1) identify and optimize practices that could underpin no-till systems that don't rely on herbicides; (2) quantify the outcomes of those practices; and (3) assess the financial, technical, and cultural barriers to adoption and implementation across a diversity of contexts (soil types, climates, production systems). For example, with cover crops, more work is needed to identify which cover crop species can be successfully terminated by a roller crimper, which species can be terminated by winter kill, and/or to identify which animals to graze, for how long, and how much to let them graze down crop biomass. Accelerating the ability of farmers to minimize tillage and reap the soil benefits — without the degenerative impacts of the chemicals used in conventional no-till — could help move the U.S. towards a more regenerative agricultural system overall.

C. Phase out industrial crop production for livestock feed and biofuels

At the largest scale, we must address the end-use of the majority of conventional corn and soy production: livestock feed and first-generation biofuels (i.e., ethanol and soy biodiesel). Continuing to cultivate industrial corn and soy on hundreds of millions of U.S. acres to feed these industries is a climate and biodiversity catastrophe. First-generation biofuels are associated with significant greenhouse gas emissions, along with other adverse effects on biodiversity and water quality.[177,178,179] And scientists warn that we must reduce our consumption of animal products and shift to plant-rich diets if we are going to avert global warming, as the livestock industry, including feed production, currently accounts for a majority of agricultural emissions and 14.5% of total global emissions.[180,181,182,183]

In some contexts, regenerative grazing practices may benefit the climate, soil health, and human health — for example, when regenerative grazing replaces conventional grazing, or when animals are integrated into small-scale, diversified cropping systems. However, the ability of regenerative grazing to mitigate emissions is limited,[184] and it is critical that support for regenerative grazing doesn't incentivize the overall expansion of cattle grazing into more land than it already occupies. The surest path to reducing the climate, air and water pollution, and other impacts of the livestock industry is to reduce overall meat and dairy consumption.

U.S. farm policy and corporate initiatives must be focused on a speedy transition away from our overproduction of meat and dairy and our overdependence on corn and soy and towards more diversified cropping systems. And in the meantime, policymakers and companies should promote approaches to animal agriculture and the cultivation of corn, soy and other row crops that are holistic, ecological, and systems-based.

D. Specific recommendations for policymakers, companies, and the regenerative agriculture community

1. Policymakers

- Any definitions of "regenerative agriculture" promulgated by federal, state, or local governments should explicitly center and prioritize transitioning away from agrochemicals.
- Federal, state, and local governments should fund and direct resources towards researching and spurring the adoption of techniques (such as roller-crimping, flame weeding, occultation, and animal grazing) that may be able to replace herbicides to effectively suppress weeds in no-till and minimal-till systems, accelerating the ability of farmers to reap the benefits of reduced tillage without needed to rely on degenerative chemical inputs.
- USDA should increase incentives for farm operations that eliminate or deeply reduce the use of synthetic pesticides and fertilizers, and focus more resources on promoting and measuring reductions in use, to help accelerate the adoption of truly regenerative agriculture. It is also critical, when tracking or measuring pesticide use reductions, to do so in terms of decreasing risk and toxicity, and not decreasing pounds of active ingredient.[185]
- USDA should add the Natural Resource Conservation Service (NRCS) Conservation Practice Standard 595, "Pest Management Conservation System,"[186] to the Climate-Smart Agriculture and Forestry (CSAF) Mitigation and Activities List, making it eligible to receive money and resources allocated to climate-smart agriculture.
- Additionally, USDA should update Conservation Practice Standard 595 — under "Purpose" — to recognize that reducing and eliminating synthetic pesticides averts greenhouse gas emissions and protects the soil microorganisms essential in the process of fixing nitrogen (building fertility and mitigating N_2O emissions) and sequestering carbon.
- USDA should pursue research that evaluates the contexts in which promoting and incentivizing the adoption of standalone no-till (for example, through Conservation Practice Standard 329, "Residue and Tillage Management: No-Till") may lead to increased reliance on chemical herbicides. USDA should assess possible methods for preventing further expansion of chemical-intensive no-till.
- Congress should pass legislation as part of the Farm Bill that establishes a new conservation standard focused explicitly on reducing the use of chemical pesticides, particularly in no-till systems (e.g. the Streamlining Conservation Practice Standards Act).

- Congress should create a new training program for NRCS Technical Service Providers focused on soil health and input reduction, increasing the support available to help conventional growers significantly reduce pesticide and synthetic fertilizer use or transition to organic (e.g., by passing the Soil Care Act).
- Congress should adopt new regenerative agriculture programs that help farmers transition to perennial, agroforestry, and other diversified cropping systems as outlined in the bipartisan Innovative Practices for Soil Health Act.
- Congress should increase funding for the National Organic Program, the Organic Transitions Program, the Sustainable Agriculture Research and Education Program, and other key programs that support organic agriculture for Fiscal Year 2025 – and beyond – in alignment with the National Organic Coalition's "Appropriations Priorities: Fiscal Year 2025 Requests."[187]
- Where the assumption that no-till as a standalone practice increases soil carbon sequestration has been incorporated into materials and models, this assumption should be re-examined in light of the science, and materials and models should be updated appropriately.

2. Food manufacturers & retailers

- Corporate regenerative agriculture initiatives should explicitly center and prioritize transitioning away from agrochemicals. Companies are encouraged to set time-bound, measurable goals to phase out toxic pesticides and synthetic fertilizers and transition towards ecological, least-toxic approaches along their entire food and beverage supply chains.
- Companies should not fund or incentivize no-till as a standalone practice, as this is unlikely to achieve the stated goals of regenerative agriculture and may incentive degenerative practices. Instead, companies should provide financial and technical assistance to suppliers to support a broad transition to ecological, low-input growing systems — which may use tillage or not, depending on context.
- Companies should invest in expanding organic food and beverage offerings, recognizing that diversified organic is a leading form of regenerative agriculture. Companies should prioritize sourcing from and supporting domestic U.S. organic growers and also help non-organic growers in the supply chain transition to organic (for example, by providing incentives to transition, by offering technical assistance, by committing to price floors during transition, or by covering the cost of organic certification).
- Companies should keep in mind that there is no set definition of regenerative agriculture, allowing extensive greenwashing to occur in the regenerative space. While the term is being applied to truly regenerative farms — like regenerative organic farms — that support biodiversity, protect soils, and fight climate change, it is also frequently being applied to degenerative forms of agriculture like chemical-intensive no-till. Companies are advised to be aware of this dynamic and put appropriate safeguards in place to ensure that investments in regenerative are effective and impactful.

3. Regenerative community

- Members of the regenerative community (e.g., advocates, certifiers, technical assistance providers, farmers) should promote a nuanced understanding of tillage: that it is not universally detrimental to soil health and can be part of truly regenerative growing systems, depending on context. Conversely, be aware that uplifting strict no-till without equally prioritizing input reduction can inadvertently incentivize chemical-dependent growing systems that are at odds with regenerative goals.

- Where the assumption that no-till as a standalone practice increases soil carbon sequestration has been incorporated into materials and models, this assumption should be re-examined in light of the science, and materials and models should be updated appropriately.

- Regenerative certifications that do not already do so should evaluate and adapt their standards to prioritize agrochemical input reduction and elimination. Certification frameworks should incentivize and support growers to transition away from synthetic inputs over time, with the ultimate goal of minimizing use or eliminating those inputs entirely. It is also critical, when tracking or measuring pesticide use reduction, to do so in terms of decreasing risk and not simply decreasing pounds of active ingredient.[188]

- We encourage members of the regenerative community to understand diversified organic agriculture as a leading form of regenerative agriculture. This is already happening in many regenerative spaces but is not ubiquitous. As opposed to seeing organic and regenerative as separate, as competitors, or as fundamentally different perspectives on agriculture, we believe it is both accurate and strategic to consider diversified organic as one type of growing system that falls under the broad umbrella of regenerative. We encourage members of the regenerative community to recognize that supporting the National Organic Program, as well as organic researchers, farmers, and advocates, is a way to advance the goals of the regenerative movement. We must combine the momentum behind regenerative and the longstanding success of organic in order to address the climate and biodiversity crises with urgency and speed the transition to a more sustainable, equitable, and healthy food system.

APPENDIX

1. Pesticides used in corn production in 2021

Pesticides used in corn production in 2021			
	Type of Pesticide	**Acres Treated**	**Pounds Applied**
Pyraclostrobin	Fungicide	4,662,600	890,557
Propiconazole	Fungicide	6,527,640	633,181
Azoxystrobin	Fungicide	6,527,640	620,126
Prothioconazole	Fungicide	3,730,080	331,977
Trifloxystrobin	Fungicide	3,730,080	317,057
Mefentrifluconazole	Fungicide	1,865,040	201,424
Fluopyram	Fungicide	1,865,040	145,473
Other Fungicides	Fungicide	-	134,000
Tebuconazole	Fungicide	932,520	124,958
Benzovindiflupyr	Fungicide	3,730,080	96,982
Picoxystrobin	Fungicide	932,520	86,724
Pydiflumetofen	Fungicide	932,520	55,951
Cyproconazole	Fungicide	932,520	21,448
Tetraconazole	Fungicide	220,536	14,114
Fluxapyroxad	Fungicide	255,462	13,029
Glyphosate	Herbicide	73,669,080	79,926,289
Atrazine	Herbicide	60,613,800	63,886,945
Acetochlor	Herbicide	31,705,680	44,863,537
S-metolachlor	Herbicide	25,178,040	29,055,458
Metolachlor	Herbicide	2,797,560	7,128,183
2,4-D	Herbicide	8,392,680	6,772,893
Mesotrione	Herbicide	43,828,440	5,785,354
Dicamba	Herbicide	17,871,761	4,571,093
Dimethenamid	Herbicide	5,595,120	3,217,194
Other Herbicides	Herbicide	-	2,355,000
Clopyralid	Herbicide	16,785,360	1,387,590
Pendimethalin	Herbicide	932,520	939,048
Glufosinate-ammonium	Herbicide	1,865,040	865,379
Simazine	Herbicide	932,520	850,458
Paraquat	Herbicide	932,520	696,592
Tembotrione	Herbicide	6,527,640	652,764
Clethodim	Herbicide	932,520	497,966
Bicyclopyrone	Herbicide	8,392,680	302,136
Isoxaflutole	Herbicide	3,730,080	272,296
Metribuzin	Herbicide	932,520	200,492

Flumetsulam	Herbicide	6,527,640	189,302
Pyroxasulfone	Herbicide	1,865,040	169,719
Diflufenzopyr-sodium	Herbicide	3,730,080	160,393
Saflufenacil	Herbicide	1,865,040	110,037
Fluroxypyr	Herbicide	932,520	76,467
Thiencarbazone-methyl	Herbicide	3,730,080	70,872
Topramenzone	Herbicide	5,595,120	67,141
Flumioxazin	Herbicide	932,520	60,614
Rimsulfuron	Herbicide	932,520	15,853
Thifensulfuron	Herbicide	932,520	11,190
Fluthiacet-methyl	Herbicide	932,520	4,663
Halosulfuron	Herbicide	394,805	4,343
Bifenthrin	Insecticide	5,595,120	453,205
Other Insecticides	Insecticide	-	275,000
Chlorpyrifos	Insecticide	233,394	146,571
Lambda-cyhalothrin	Insecticide	3,730,080	123,093
Tebupirimiphos	Insecticide	932,520	87,657
Cyfluthrin	Insecticide	932,520	27,043
Beta-cyfluthrin	Insecticide	932,520	22,380
Tefluthrin	Insecticide	394,805	21,714
Zeta-cypermethrin	Insecticide	932,520	17,718
All Other Pesticides	Other	932,520	329,000
Totals			**260,357,642**

Notes:
1. Table generated by C. Benbrook drawing on the Pesticide Use Data System (PUDS)
2. Data in PUDS is from the USDA QuikStat system and is based on periodic surveys.

2. Pesticides used in soy production in 2020

	Type of Pesticide	Acres Treated	Pounds Applied
Azoxystrobin	Fungicide	5,834,780	659,330
Propiconazole	Fungicide	5,834,780	612,652
Pyraclostrobin	Fungicide	5,001,240	605,150
Picoxystrobin	Fungicide	2,500,620	345,086
Other Fungicides	Fungicide	-	300,000
Fluxapyroxad	Fungicide	4,167,700	254,230
Tetraconazole	Fungicide	3,334,160	253,396
Prothioconazole	Fungicide	2,500,620	185,046
Trifloxystrobin	Fungicide	2,500,620	170,042
Difenoconazole	Fungicide	1,667,080	155,038
Pydiflumetofen	Fungicide	1,667,080	143,369
Mefentrifluconazole	Fungicide	833,540	85,021
Cyproconazole	Fungicide	1,667,080	56,681
Benzovindiflupyr	Fungicide	1,667,080	45,011
Glyphosate	Herbicide	78,583,072	98,392,272

S-metolachlor	Herbicide	15,837,260	20,699,299
Dicamba	Herbicide	30,189,739	17,080,870
2,4-D	Herbicide	25,187,671	16,110,578
Acetochlor	Herbicide	7,501,860	8,207,035
Glufosinate-ammonium	Herbicide	14,170,180	7,722,748
Metolachlor	Herbicide	4,167,700	4,609,476
Metribuzin	Herbicide	15,003,720	4,111,019
Fomesafen	Herbicide	13,336,640	3,508,370
Sulfentrazone	Herbicide	17,504,340	3,500,868
Paraquat	Herbicide	4,167,700	2,321,409
Dimethenamid	Herbicide	4,167,700	1,971,322
Pyroxasulfone	Herbicide	13,336,640	1,760,436
Clethodim	Herbicide	14,170,180	1,686,251
Pendimethalin	Herbicide	1,667,080	1,440,357
Atrazine	Herbicide	833,540	1,109,442
Flumioxazin	Herbicide	8,335,400	983,577
Trifluralin	Herbicide	833,540	672,667
Imazethapyr	Herbicide	11,669,560	606,817
Other Herbicides	Herbicide	-	330,000
Bentazon	Herbicide	403,562	311,147
Fluazifop-P-butyl	Herbicide	3,334,160	296,740
Saflufenacil	Herbicide	8,335,400	200,050
Cloransulam-methyl	Herbicide	5,834,780	151,704
Acifluorfen, sodium	Herbicide	400,946	136,322
Chlorimuron-ethyl	Herbicide	5,834,780	128,365
Lactofen	Herbicide	833,540	120,863
Mesotrione	Herbicide	833,540	91,689
Thifensulfuron	Herbicide	1,667,080	36,676
Imazamox	Herbicide	833,540	25,840
Diquat dibromide	Herbicide	833,540	24,173
Quizalofop-P-ethyl	Herbicide	358,836	20,812
Fluthiacet-methyl	Herbicide	3,334,160	20,005
Carfentrazone-ethyl	Herbicide	428,492	7,284
Rimsulfuron	Herbicide	138,750	4,162
Flumiclorac-pentyl	Herbicide	115,625	2,081
Acephate	Insecticide	833,540	904,391
Chlorpyrifos	Insecticide	833,540	411,769
Bifenthrin	Insecticide	4,167,700	304,242
Other Insecticides	Insecticide	-	206,000
Lambda-cyhalothrin	Insecticide	6,668,320	180,045
Methoxyfenozide	Insecticide	833,540	121,697
Imidacloprid	Insecticide	1,667,080	86,688
Chlorantraniliprole	Insecticide	833,540	55,847

Cyfluthrin	Insecticide	833,540	49,179
Beta-cyfluthrin	Insecticide	1,667,080	40,010
Thiamethoxam	Insecticide	833,540	27,507
Zeta-cypermethrin	Insecticide	1,667,080	20,005
Alpha cypermethrin	Insecticide	833,540	17,504
Diflubenzuron	Insecticide	302,117	9,366
Cypermethrin	Insecticide	225,000	8,325
Sodium chlorate	Other	103,155	449,550
Flutriafol	Other	833,540	70,851
Other Pesticides	Other	-	12,000
Indolebutyric acid	Other	1,667,080	3,334
Totals			**205,251,089**

Notes:
1. Table generated by C. Benbrook drawing on the Pesticide Use Data System (PUDS)
2. Data in PUDS is from the USDA QuikStat system and is based on periodic surveys.

3. Trends in herbicide use in corn and soy production in the U.S.:

		1996	2001	2021
Corn	**Glyphosate**	2,482,960	7,354,428	79,962,289
	Atrazine	60,342,702	66,671,729	63,886,945
	Acetochlor	33,689,254	34,203,233	44,863,537
	Metolachlor*	46,425,711	27,030,915	36,183,641
	2,4-D	3,653,337	3,020,798	6,772,893
	Dicamba	6,258,188	3,464,120	4,571,093
	Paraquat	718,929	547,191	696,592

		1996	2001	2020
Soy	**Glyphosate**	10,940,984	46,732,777	98,392,272
	Metolachlor*	5,316,207	1,374,661	25,308,775
	Dicamba	0	0	17,080,870
	2,4-D	3,559,251	1,326,227	16,110,578
	Atrazine	0	0	1,109,442
	Acetochlor	0	0	8,207,035
	Paraquat	428,218	0	2,321,409

Notes:
1. Table generated by drawing on the Pesticide Use Data System (PUDS)
2. Data in PUDS is from the USDA QuikStat system and is based on periodic surveys.

*Represents the aggregate amount of S-metolachlor and metolachlor.

4. Methodology

1. Soy: Herbicides

a. Lowest possible percentage of no/minimum till soy that is herbicide-dependent:

- Data points:
  - Total soy acres: 83.6 million[i]
  - Share of total soy acres that are no/minimum-till acres: 62% (51.832 million)[i]
  - Share of total soy acres that report no herbicide use: 4% (3.344 million)[i]
- Calculation:
  - Fewest possible soy acres that are no/minimum till AND use herbicides: 51.832 - 3.344 = **48.448 million acres**
  - Lowest possible percent of no/minimum till soy acres that are herbicide dependent: 48.448/51.832 = **93.5%**
  - Lowest possible percent of total soy acres that are no/minimum till AND herbicide dependent: 62% - 4% = **58%**
- **Estimated pounds of herbicide used on no/minimum till soy annually:**
- Data points:
  - Total soy acres: 83.6 million[i]
  - Share of total soy acres that are no/minimum-till acres: 62% (51.832 million)[i]
  - Share of total soy acres that report no herbicide use: 4% (3.344 million)[i]
  - Annual herbicide use in soy: 198,402,728 lbs[ii]
- Assumptions
  - Here, we assumed that the soy acres that do not report herbicide use are split evenly between the categories of no/minimum till and standard tillage acres. This would mean:
    - 60% of soy acres (50.16 million acres) are no/min-till AND use herbicides (these acres referred to as 'N' moving forward)
    - 36% of soy acres (30.096 million acres) use standard tillage AND use herbicide (these acres will be referred to as 'T' moving forward)
    - 4% of soy acres (3.344 million acres) do not use herbicides (these acres will be referred to as 'H' moving forward); half of these are no/min-till.
  - We assumed that no-till acres use 10% (1.1x) more herbicides than tilled acres. Studies suggest herbicide use increases 10% - 41% alongside the adoption of no-till in conventional systems.[iii,iv] Thus, an assumption of 10% increase is conservative and likely underestimates actual usage.
- Calculations:
  - Equation 1:
    - Using x to represent the application rate in lbs/acre for N acres and y to represent the application rate in lbs/acre for T acres:
    - (# of N acres)(application rate in lbs/acre) + (# of T acres)(application rate in lbs/acre) + (# of H acres)(application rate in lbs/acres) = total lbs of herbicide used

- (50.16)(x) + (30.096)(y) + (3.344)(0) =198.403
- 50.16x + 30.096y =198.403

- Equation 2:
  - x = 1.1y
- Solving for rates per acre (x and y):
  - 50.16(1.1y)+ 30.096y =198.403
  - 85.272y = 198.403
  - y = 2.33 lbs/acre
  - x = 1.1(2.32) = 2.55 lbs/acre
- Solving for total herbicide use in no/minimum till soy systems and the increased use of herbicides due to no/minimum-till management:
- 50.16 million acres x 2.55 lbs/acre = **127,908,000 lbs used on no-till soy**
- 127,908,000/198,402,728 = .644 = **64.4% of the total herbicides used on soy can be attributed to no/minimum till soy acres**
- 127,908,000 lbs - (50.16 million acres x 2.32 lbs/acre) = 127,908,000 - 116,371,200 = **11,536,800 lbs of additional herbicides are used annually due to the use of no/minimum-till management instead of conventional tillage**

Sources

I. USDA. 2023. NASS Highlights, 2023 Agriculture Chemical Use Survey: Soybeans. U.S. Department of Agriculture: Washington, D.C. May.

II. Pesticide Use Data System (PUDS), based on USDA QuikStat surveys

III. Pittelkow, C. M., Linquist, B. A., Lundy, M. E., Liang, X., Van Groenigen, K. J., Lee, J., & Van Kessel, C. 2015. When does no-till yield more? A global meta-analysis. Field Crops Research. 183: 156-168;

IV. Hristovska, T.; Watkins, K.B.; Anders, M.M. 2013. An economic risk analysis of no-till management for the rice-soybean rotation system used in Arkansas. Journal of Soil and Water Conservation. 68: 132–137.

2. Corn: Herbicides

a. Lowest possible percentage of no/minimum till corn that is herbicide-dependent:

- Data points
  - Total corn acres: 93.4 million[i]
  - Share of total corn acres that are no/minimum till acres: 59% (55.106 million)[i]
  - Share of total corn acres that report no herbicide use: 4% = (3.736 million)[i]

- Calculations
  - Fewest possible corn acres that are no/minimum till AND using herbicides: 55.106 - 3.736 = **51.37 million acres**
  - Lowest possible percent of total no/minimum till corn acres that are herbicide dependent: 51.37/55.106 = **93.22%**
  - Lowest possible percent of total corn acres that are no/minimum till AND herbicide dependent: **59% - 4% = 55%**

b. Estimated pounds of herbicide used on no/minimum till corn annually:

- Data points:
  - Total corn acres: 93.4 million[i]
  - Share of total corn acres that are no/minimum till acres: 59% (55.106 million)[i]
  - Share of total corn acres that report no herbicide use: 4% = (3.736 million)[i]
  - Total use of herbicides reported for corn: 255,167,260 lbs[ii]

- Assumptions:
  - Here, we assumed that the corn acres that did not report herbicide use are split evenly between the categories of no-/min-till and standard tillage acres. This would mean:
    - 57% of corn acres (53.24 million acres) are no/min-till AND use herbicides (these acres referred to as 'N' moving forward)
    - 39% of corn acres (36.43 million acres) use standard tillage AND use herbicide (these acres referred to as 'T' moving forward)
    - 4% of corn acres (3.74 million acres) do not use herbicides (these acres referred to as 'H' moving forward)
  - We assumed that no-till acres use 10% (1.1x) more herbicides than tilled acres. Studies suggest herbicide use increases 10% - 41% alongside the adoption of no-till in conventional systems.[iii,iv] Thus, an assumption of 10% increase is conservative and likely underestimates actual usage.

- Calculations:
  - Equation 1:
    - Using x to represent the application rate in lbs/acre for N acres and y to represent the application rate in lbs/acre for T acres:
    - (# of N acres)(application rate in lbs/acre) + (# of T acres)(application rate in lbs/acre) + (# of H acres)(application rate in lbs/acres) = total lbs of herbicide used
    - $(53.24)(x) + (36.43)(y) + (3.74)(0) = 255.167$
    - $53.24x + 36.43y = 255.167$
  - Equation 2:
    - $x = 1.1y$
    - Solving for rate per acre:
    - $53.24(1.1y) + 36.43y = 255.167$
    - $94.99y = 255.167$
    - y = 2.69 lbs/acre
    - x = 1.1(2.69) = 2.96 lbs/acre
  - Solving for total herbicide use in no/minimum till soy systems and the increased use of herbicides due to no/minimum-till management:
  - 53.24 million acres x 2.96 lbs/acre = **157,590,400 lbs used on no-till corn**
    - 157,590,400/255,167,260 = 61.8% of total herbicides used on corn can be attributed to no/minimum till acres)
  - 157,590,400 lbs - (53.24 million acres x 2.69 lbs/acre) = 157,590,400 - 143,215,600 = **14,374,800 lbs of additional herbicides are used annually due to the use of no/minimum-till management instead of conventional tillage**

Sources

I. USDA. 2022. NASS Highlights, 2021 Agriculture Chemical Use Survey: Corn. U.S. Department of Agriculture: Washington, D.C. May.

II. Pesticide Use Data System (PUDS) (based on USDA QuikStat surveys)

III. Pittelkow, C. M., Linquist, B. A., Lundy, M. E., Liang, X., Van Groenigen, K. J., Lee, J., ... & Van Kessel, C. 2015. When does no-till yield more? A global meta-analysis. Field Crops Research. 183: 156-168.

IV. Hristovska, T.; Watkins, K.B.; Anders, M. M. 2013. An economic risk analysis of no-till management for the rice-soybean rotation system used in Arkansas. Journal of Soil and Water Conservation. 68: 132–137.

3. Corn and Soy Combined: Herbicides

- Data points
  - See Sections 1 and 2 above
- Calculations:
  - Total corn and soy acres managed as no/minimum till: 55.106 + 51.832 = **106.938 million acres**
  - Total corn and soy acres managed as no/minimum till and using herbicide: 51.27 + 48.448 million acres = **99.818 million acres**
  - Lowest possible percent of no/minimum till corn and soy acres that are using herbicides: **93.3%**
  - Estimated total pounds of herbicide used annually in no/minimum till corn and soy: **285,498,400 lbs**
  - Estimated pounds of additional herbicide used in corn and soy annually due to no/minimum till management: **25,911,600 lbs**

4. Corn and Soy: Glyphosate Use

- Data point:
  - Glyphosate represents approximately 39.5% of annual herbicide use in corn and soy[i]
  - Estimated total pounds of herbicide used annually on no/minimum till corn and soy: 285,498,400 lbs[ii]
- Assumption:
  - Glyphosate likely represents 39.5% of annual herbicide use in no/minimum till corn and soy
- Calculations:
  - Glyphosate used annually in no/min-till corn and soy: (.395) x (285,498,400) = **112,771, 868 lbs**

Sources:

I. Pesticide Use Data System (PUDS) (based on USDA QuikStat surveys)

II. See Section 3 above.

5. Genetically Engineered (GE) Seeds

a. Soy

- Data points
  - Total soy acres: 83.6 million[i]
  - Share of soy acres that are no/minimum-till: 62% (51.832 million acres)[i]
  - Share of soy acres reporting no use of GE seeds: 5% (4.18 million acres)[ii]
- Calculations
  - Fewest possible soy acres that no/minimum-till AND using GE seeds: 51.832 - 4.18 = **47.652 million acres**
  - Lowest possible percent of no/minimum till soy acres that uses GE seeds: 47.652/51.832 = **91.9%**

b. Corn

- Data points:
  - Total corn acres: 93.4 million[iii]
  - Share of corn acres that are no/minimum till: 59% (55.106 million)[iii]
  - Share of corn acres that report no use of GE seeds: 7% (6.538 million acres)[ii]
- Calculations:
  - Fewest possible corn acres that are no/minimum till AND using GE seeds: 55.106 - 6.538 = **48.568 million acres**
  - Lowest possible percent of no/minimum till corn acres that use GE seeds: 48.568/55.106 = **88.1%**

c. Corn and Soy Combined

- Total no/minimum-till corn and soy acres that use GE seeds: 47.652 + 48.568 = **96.22 million acres**
- Lowest possible percent of no/minimum-till corn and soy acres using GE seeds: 96.22 / 106.938 = **89.9%**

Sources

I. USDA. 2023. NASS Highlights, 2023 Agriculture Chemical Use Survey: Soybeans. U.S. Department of Agriculture: Washington, D.C. May.

II. USDA Economic Research Service. Adoption of Genetically Engineered Crops in the U.S. U.S. Department of Agriculture: Washington, D.C. Webpage. Accessed July 18, 2024.

III. USDA. 2022. NASS Highlights, 2021 Agriculture Chemical Use Survey: Corn. U.S. Department of Agriculture: Washington, D.C. May.

6. Highly Hazardous Pesticides (HHPs)

a. Estimated highly hazardous herbicide use in no/minimum-till soy

- Data points:
  - Number of highly hazardous herbicides used in soy: 11[i,ii]
  - Total pounds of highly hazardous herbicides used in soy: 138,606,781 lbs[i,ii]
- Assumptions:
  - We estimate that 64.4% of herbicide use in soy can be attributed to no/minimum-till acres (see Section 1b above). For this calculation, we assumed that this ratio holds true for highly

hazardous herbicides, and that 64.4% of highly hazardous herbicide use in soy can be attributed to no/minimum-till acres.

- Calculations:
  - (.644) x (138,606,781) = **89,262,767 lbs of highly hazardous herbicides used annually on no/minimum till soy**
  - **Estimated highly hazardous herbicide use in no/minimum till corn**
- Data points:
  - Number of highly hazardous herbicides used in corn: 12[i,ii]
  - Total pounds of highly hazardous herbicides used in corn: 135,456,603 lbs[i,ii]
- Assumptions:
  - We estimate that 61.8% of herbicide use in corn can be attributed to no/minimum-till acres (see Section 2b above). For this calculation, we assumed that this ratio holds true for highly hazardous herbicides, and that 61.8% of highly hazardous herbicide use in corn can be attributed to no/minimum-till acres.
- Calculations:
  - (.618) x (135,456,603) = **83,712,181 lbs of highly hazardous herbicides used annually on no/minimum till corn**

b. Estimated highly hazardous herbicides use no/minimum till corn and soy:

- Total pounds of highly hazardous herbicides used in corn and soy annually: 138,606,781 + 135,456,603 = **274, 063,384 lbs**
- Total pounds of highly hazardous herbicide attributable to no/minimum till corn and soy annually: 89,262,767 + 83,712,181 = **172,974,948 lbs**
- Percentage of highly hazardous herbicide use in corn and soy that is attributable to no/minimum till acres: **63%**

Sources:

I. Pesticide Use Data System (PUDS) (based on USDA QuikStat surveys)

II. Pesticide Action Network International. 2021. PAN International List of Highly Hazardous Pesticides. Pesticide Action Network International: Hamburg, Germany. March.

7. Corn: Neonicotinoids

- Data points:
  - Percent of corn acres that are no/minimum till: 59%[i]
  - Total pounds of neonicotinoids used to treat corn seeds annually: 4,189,605 lbs[ii]
  - Percent of corn acres that use neonicotinoid-coated seeds: 79 - 100%[iii]
- Assumptions:
  - At the upper end of the range, if 100% of no/minimum till corn acres use neonicotinoid-coated seeds, then approximately 59% of total neonicotinoid use as seeds coating in corn can be attributed to no/minimum till acres.

- Calculation
  - (.59) x (4,189,605) = **2,471,866 lbs of neonicotinoids used annually to treat seeds for no/minimum till corn**

Sources

I. USDA. 2022. NASS Highlights, 2021 Agriculture Chemical Use Survey: Corn. U.S. Department of Agriculture: Washington, D.C. May.

II. US Geological Survey, U.S. Geological Survey Pesticide National Synthesis Project. (Note: We used totals from 2014, as the USGS stopped collecting data on pesticide seed treatments in 2015, creating a significant gap in data beyond that point.)

III. Douglas, M. R., & Tooker, J. F. 2015. Large-scale deployment of seed treatments has driven rapid increase in use of neonicotinoid insecticides and preemptive pest management in US field crops. Environmental Science & Technology. 49(8): 5088-5097.

8. Estimated Annual Greenhouse Gas Emissions: Production of Herbicides for No/Minimum Till Corn & Soy

- Data points:
  - Estimated herbicide use attributable to no-till corn and soy: 285,498,400 lbs (129,499,895 kg)[i]
  - Estimated herbicide use attributable to no-till corn: 157,590,400 lbs (71,481,803 kg)[ii]
  - Estimated glyphosate use attributable to no-till corn and soy: 112,771,868 lbs (51,152,458 kg)[iii]
  - Low emissions scenario: 18 kg CO2e per kg of herbicide[iv]
  - High emissions scenario: 27 kg of CO2e per kg of herbicide[v]
  - Glyphosate emissions: 31.29 kg of CO2e equivalent per kg of glyphosate[iv]
  - Average emissions of a car on the road for a year: 4.6 metric tons CO_2e[v]
- Calculations
  - Low emissions scenario, herbicide production, no/minimum till corn and soy:
    - (18 kg CO_2e per kg herbicide) x (129,499,895 kg of herbicide) = 2,330,998,110 kg CO_2e = **2,330,998 metric tons of CO_2e**
  - High emissions scenario, herbicide production, no/minimum till corn and soy:
    - (27 kg CO_2e per kg herbicide) x (129,499,895 kg of herbicide) = 3,496,497,165 kg CO_2e = **3,496,497 metric tons of CO_2e**
  - Low emissions scenario, herbicide production, no/minimum till corn only:
    - (18 kg CO_2e per kg of herbicide) x (71,481,803 kg of herbicide) = 1,286,672,454 kg CO_2e = **1,286,672 metric tons of CO_2e**
  - High emissions scenario, herbicide production, no/minimum till corn only:
    - (27 kg CO_2e per kg of herbicide) x (71,481,803 kg of of herbicide) = 1,930,008,681 kg CO_2e = **1,930,009 metric tons of CO_2e**
  - Estimated emissions, glyphosate production, no/minim-till corn and soy:
    - (31.29 kg CO_2e per kg of glyphosate) x (51,152,458 kg of glyphosate) = 1,600,560,411 kg CO_2e = **1,600,560 metric tons of CO_2e**

- High emission scenario, herbicide production, no/minimum-till corn and soy – compared to emissions of cars on the road for a year:
    - 3,496,497 metric tons of CO_2e / 4.6 metric tons of CO_2e = **760,108 cars on the road for a year**

Sources

I. See Section 3, above

II. See Section 2, above

III. See Section 4, above

IV. Audsley, E., Stacey, K., Parsons, D.J., Williams, A.G., 2009. Estimation of the Greenhouse Gas Emissions from Agricultural Pesticide Manufacture and Use. Cranfield University: Bedford, U.K.

V. U.S. Environmental Protection Agency. Greenhouse Gas Emissions from a Typical Passenger Vehicle. U.S. EPA: Washington, D.C.

9. Estimated Annual Greenhouse Gas Emissions: Synthetic Nitrogen Fertilizer (N) in No-Till Corn

- Data points:
  - Total US N fertilizer consumption annually: 11.6 million metric tonsi
  - Total GHG emissions associated with annual US N consumption (manufacturing, transportation, and soil emissions): 115.5 ± 52.9 million metric tons CO2e annually[i]
  - Total corn acres: 93.4 million[ii]
  - Share of corn acres that are no/minimum till: 59% (55.106 million)[ii]
  - Share of of corn acres that receive N: 95% (88.73 million)[ii]
  - Share of corn acres that do not receive N: 5% (4.67 million)[ii]
  - When N is applied to corn, average rate of application : 150 lbs/acre (68 kg per acre)[ii]
  - Average emissions of a car on the road for a year: 4.6 metric tons CO_2e[iii]
- Assumptions:
  - For this estimate, we assumed that no/minimum till cron acres that apply nitrogen fertilizer apply it at approximately the same rate as conventional corn acres using tillage. Thus, we used the average application rate (68 kg per acre) reported by USDA.
- Calculations:
  - Average emissions per ton N, low scenario:
    - (115.5 - 52.9 million metric tons CO_2e) / (11.6 million metric tons N) = **5.4 metric tons of CO_2e per metric ton of N**
  - Average emissions per ton N, high scenario:
    - (115.5 + 52.9 million metric tons CO_2e) / (11.6 million metric tons N) = **14.5 metric tons of CO_2e per metric ton N**
  - Fewest possible corn acres that are no/minimum till AND apply N:
    - 55.106 - 4.67 = **50.436 million acres**
  - Estimated amount of N applied to no/min-till corn annually:
    - 50.436 million acres x 68 kg/acre = 3,429,648,000 kg = **3.4 million metric tons N**

- Estimated emissions range for N applied to no/minimum till corn annually:
  - (5.4 metric tons of CO2e per metric ton N x 3.4 million metric tons N) to (14.5 metric tons of CO_2e per metric ton N x 3.4 million metric tons N) = **18.4 million to 49.3 million metric tons CO_2e annually**
- Compare to cars on the road for a year
  - (18.4 million metric tons tons of CO_2e / 4.6 metric tons of CO_2e) to (49.3 million metric tons of CO_2e / 4.6 metric tons of CO_2e) = **between 4 million and 10,717,391 million cars on the road for a year**

Sources

I. Menegat, S., Ledo, A. & Tirado, R. 2022. Sci Rep 12, 14490 (2022). Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture. Scientific Reports. 12: 14490. See Table 1.

II. USDA. 2022. NASS Highlights, 2021 Agriculture Chemical Use Survey: Corn. U.S. Department of Agriculture: Washington, D.C. May.

III. U.S. Environmental Protection Agency. Greenhouse Gas Emissions from a Typical Passenger Vehicle. U.S. EPA: Washington, D.C.

10. Cover crop comparison

a. Potential of cover crops to mitigate emissions, based on meta-reviews

- Data points
  - Study #1: The potential of cover crops to mitigate emissions: 103 Tg CO2e per year if adopted on 88Mha[i]
  - Study #2: The potential of cover crops to mitigate emissions: 270 - 430 kg C per hectare per year[ii]
  - Study 3: The potential of cover crops to mitigate emissions: 0.56 Mg C per hectare per year[iii]
- Assumptions
  - To convert a mass of carbon (C) to a mass of CO_2e, multiply by a factor of 3.67[iv]
- Calculations
  - Study #1
    - 103 Tg CO_2e per year = 103 million metric tons CO_2e per year
    - 88mha = 217,452,735 acres
    - (103 million metric tons CO_2e per year) / (217.452 million acres) = **.47 metric tons CO_2e per acre per year**
  - Study #2:
    - 270 to 430 kg C = (270 kg C x 3.67) to (430 kg C x 3.67) = 990.9 to 1578.1 kg CO_2e
    - 1 hectare = 2.47 acres
    - (990.9 kg CO_2e / 2.47) to (1578.1CO_2e / 2.47) = 401.2 to 638.9 kg CO_2e per acre per year = **.4 to .64 metric tons CO_2e per acre per year**

- Study #3
    - .56 Mg C = .56 metric tons C
    - (.56 metric tons C x 3.67) = 2.05 metric tons CO_2e
    - 1 hectare = 2.47 acres
    - 2.05 metric tons CO_2e per hectare per year / 2.47 = **.83 metric tons CO_2e per acre per year**
- Overall range from the three studies:
    - Cover crops, as a broad average, are likely mitigate .4 to .83 metric tons CO_2e per acre year

b. Potential of eliminating pesticides and fertilizers in no-till corn to mitigate emissions

- Data points:
    - Fewest possible no/minimum till corn acres using herbicides: 51.37 million acres[v]
    - Estimated emissions from the production of herbicides for no/minimum till corn: 1.29 million metric tons to 1.93 million metric tons CO_2e per year[vi]
    - Fewest possible no/minimum till corn acres using synthetic nitrogen fertilizer (N): 50.436 million acres[vii]
    - Estimated emissions from synthetic nitrogen fertilizer use in no/minimum-till corn: 18.4 million to 49.3 million metric tons CO_2e per year[vii]
- Calculations :
    - Pesticides: (1.29 million metric tons CO_2e / 51.37 million acres) to (1.93 million metric tons CO_2e / 51.37 million acres) = .025 to .038 metric tons CO_2e per acre per year
    - Fertilizer: (18.4 million metric tons CO_2e / 50.436 million acres) to (49.3 million metric tons CO_2e / 50.436 million acres) = .36 to .98 metric tons CO_2e per acre per year
    - Eliminating herbicide and synthetic fertilizer use in no-till corn could avert **.39 to 1.02 metric tons CO_2e per acre per year**

Sources:

I. Fargione, J.E. et al. 2018. Natural climate solutions for the United States. Science Advances. 4 (11).

II. Bolinder, M.A., Crotty, F., Elsen, A. et al. 2020. The effect of crop residues, cover crops, manures and nitrogen fertilization on soil organic carbon changes in agroecosystems: a synthesis of reviews. Mitigation and Adaptation Strategies for Global Change. 25: 929–952.

III. Jian, J., Du, X., Reiter, M.S., Stewart, R.D. 2020. A meta-analysis of global cropland soil carbon changes due to cover cropping. Soil Biology and Biochemistry. 143.

IV. U.S. Environmental Protection Agency. Frequent Questions: EPA's Greenhouse Gas Equivalencies Calculator. U.S. EPA: Washington, D.C.

V. See Methodology: Part 2

VI. See Methodology: Part 8

VII. See Methodology: Part 9

5. Health impacts of top herbicides in U.S. corn and soy production: Sources and citations

Glyphosate

- **Cancer**
  - International Agency for Research on Cancer. IARC Monograph on Cancer. World Health Organization: Geneva, Switzerland. Webpage. Accessed October 2, 2024. https://www.iarc.who.int/featured-news/media-centre-iarc-news-glyphosate/
  - Zhang, L., et al. 2019. Exposure to glyphosate-based herbicides and risk for non-Hodgkin lymphoma: A meta-analysis and supporting evidence. Reviews in Mutation Research. 781: 186 - 206. https://www.sciencedirect.com/science/article/abs/pii/S1383574218300887

- **Genotoxicity**
  - Kwiatkowska, M., Reszka, E., Woźniak, K., Jabłońska, E., Michałowicz, J., Bukowska, B. 2017. DNA damage and methylation induced by glyphosate in human peripheral blood mononuclear cells (in vitro study). Food and Chemical Toxicology. 105: 93-98. https://pubmed.ncbi.nlm.nih.gov/28351773/
  - Woźniak, E., Sicińska, P., Michałowicz, J., Woźniak, K., Reszka, E., Huras, B., Zakrzewski, J., Bukowska, B. 2018. The mechanism of DNA damage induced by Roundup 360 PLUS, glyphosate and AMPA in human peripheral blood mononuclear cells: Genotoxic risk assessment. Food and Chemical Toxicology. 120: 510-522. https://www.sciencedirect.com/science/article/abs/pii/S0278691518304800
  - Alvarez-Moya, C., Reynoso-Silva, M. 2023. Assessment of genetic damage induced via glyphosate and three commercial formulations with adjuvants in human blood cells. International Journal of Molecular Sciences. 24(5): 4560. https://doi.org/10.3390/ijms24054560

- **Reproductive Toxicity:**
  - Silver, M. et al. 2021. Prenatal exposure to glyphosate and its environmental degradate, aminomethylphosphonic acid (AMPA), and preterm birth: A nested case–control study in the PROTECT Cohort (Puerto Rico). Environmental Health Perspectives. 129(5). https://ehp.niehs.nih.gov/doi/10.1289/EHP7295
  - Parvez, S., Gerona, R.R., Proctor, C. et al. 2018. Glyphosate exposure in pregnancy and shortened gestational length: a prospective Indiana birth cohort study. Environmental Health. 17 (23). https://doi.org/10.1186/s12940-018-0367-0
  - Nerozzi, C., Recuero, S., Galeati, G. et al. 2020. Effects of Roundup and its main component, glyphosate, upon mammalian sperm function and survival. Scientific Reports. 10: 11026. https://doi.org/10.1038/s41598-020-67538-w
  - Tajai, P., Pruksakorn, D., Chattipakorn, S. C., Chattipakorn, N., Shinlapawittayatorn, K. 2023. Effects of glyphosate-based herbicides and glyphosate exposure on sex hormones and the reproductive system: From epidemiological evidence to mechanistic insights. Environmental Toxicology and Pharmacology. 102. https://www.sciencedirect.com/science/article/abs/pii/S1382668923001941
  - Araújo-Ramos, A.T., Passoni, M.T., Romano, M.A., Romano, R.M., Martino-Andrade, A.J. 2021. Controversies on endocrine and reproductive effects of glyphosate and glyphosate-based herbicides: A mini-review. Frontiers in Endocrinology. 12: 627210. https://pmc.ncbi.nlm.nih.gov/articles/PMC8006305/

- **Developmental/birth defects:**
  - U.S. EPA. 2017. Glyphosate: Draft Human Health Risk Assessment in Support of Registration Review. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2009-0361-0068
  - Rappazzo, K.M., et al. 2019. Maternal residential exposure to specific agricultural pesticide active ingredients and birth defects in a 2003-2005 North Carolina birth cohort. Birth Defects Reseach. 111(6): 312-323. https://pubmed.ncbi.nlm.nih.gov/30592382/
- **Liver & kidney impacts:**
  - U.S. EPA. 2017. Glyphosate: Draft Human Health Risk Assessment in Support of Registration Review. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2009-0361-0068
  - Mills, Paul J. et al. 2020. Glyphosate excretion is associated with steatohepatitis and advanced liver fibrosis in patients with fatty liver disease. Clinical Gastroenterology and Hepatology. 18 (3): 741 - 743. https://www.cghjournal.org/article/S1542-3565(19)30361-1/fulltext
  - Han, K., Gao, L., Xu, H. et al. 2024. Analysis of the association between urinary glyphosate exposure and fatty liver index: A study for US adults. BMC Public Health. 24: 703. https://doi.org/10.1186/s12889-024-18189-3
  - Mesnage, R., Renney, G., Séralini, G.E. et al. 2017. Multiomics reveal non-alcoholic fatty liver disease in rats following chronic exposure to an ultra-low dose of Roundup herbicide. Scientific Reports. 7: 39328. https://doi.org/10.1038/srep39328
  - Eskenazi, B., et al. 2023. Association of lifetime exposure to glyphosate and aminomethylphosphonic acid (AMPA) with liver inflammation and metabolic syndrome at young adulthood: Findings from the CHAMACOS Study. Environmental Health Perspectives. 131(3). https://ehp.niehs.nih.gov/doi/full/10.1289/EHP11721
- **Endocrine disruption:**
  - Araújo-Ramos, A.T., Passoni, M.T., Romano, M.A., Romano, R.M., Martino-Andrade, A.J. 2021. Controversies on endocrine and reproductive effects of glyphosate and glyphosate-based herbicides: A mini-review. Frontiers in Endocrinology. 12: 627210. https://pmc.ncbi.nlm.nih.gov/articles/PMC8006305/
  - Altamirano, G.A., Delconte, M.B., Gomez, A.L., Ingaramo, P.I., Bosquiazzo, V.L., Luque, E.H., Muñoz-de-Toro, M., Kass, L. 2018. Postnatal exposure to a glyphosate-based herbicide modifies mammary gland growth and development in Wistar male rats. Food and Chemical Toxicology. 118:111-118. https://pubmed.ncbi.nlm.nih.gov/29746933/
- **Irritant/sensitizer:**
  - U.S. EPA. 2017. Glyphosate: Draft Human Health Risk Assessment in Support of Registration Review. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2009-0361-0068
- **GI/Gut microbiome impacts:**
  - Lyydia, L., Tuomas, T., Marjo, H., Irma, S., Kari, S., Suvi, R., Puigbò, P. 2021. Classification of the glyphosate target enzyme (5-enolpyruvylshikimate-3-phosphate synthase) for assessing sensitivity of organisms to the herbicide. Journal of Hazardous Materials. 408: 124556. https://www.sciencedirect.com/science/article/pii/S0304389420325462
  - Walsh, L., Hill, C., Ross, R.P. 2023. Impact of glyphosate (Roundup™) on the composition and functionality of the gut microbiome. Gut Microbes. 15(2) :2263935. https://pmc.ncbi.nlm.nih.gov/articles/PMC10561581/
  - Samsel, A., & Seneff, S. 2013. Glyphosate's suppression of cytochrome P450 enzymes and amino acid biosynthesis by the gut microbiome: Pathways to modern diseases. Entropy. 15(4): 1416-1463. https://doi.org/10.3390/e15041416

- **Metabolic syndrome:**
  - Eskenazi, B., et al. 2023. Association of lifetime exposure to glyphosate and aminomethylphosphonic acid (AMPA) with liver inflammation and metabolic syndrome at young adulthood: Findings from the CHAMACOS Study. Environmental Health Perspectives. 131(3). https://ehp.niehs.nih.gov/doi/full/10.1289/EHP11721
  - Glover, F., Jean-Baptiste, O., Del Giudice, F., Belladelli, F., Seranio, N., Muncey, W., & Eisenberg, M. L. 2023. The association between glyphosate exposure and metabolic syndrome among U.S. adults. Human and Ecological Risk Assessment: An International Journal. 29(9–10): 1212–1225. https://doi.org/10.1080/10807039.2023.2256886

Dicamba

- **Cancer**:
  - Samanic et al. 2006. Cancer incidence among pesticide applicators exposed to dicamba in the Agricultural Health Study. Environmental Health Perspectives. 114 (10): 1521 - 1526. https://ehp.niehs.nih.gov/doi/full/10.1289/ehp.9204
  - Lerro, C.C. et al. 2020. Dicamba use and cancer incidence in the Agricultural Health Study: An updated analysis. International Journal of Epidemiology. 49(4): 1326–1337, https://doi.org/10.1093/ije/dyaa066
- **Genotoxic:**
  - González, N.V., Soloneski, S., Larramendy, M. L. 2006. Genotoxicity analysis of the phenoxy herbicide dicamba in mammalian cells in vitro. Toxicology in Vitro. 20(8): 1481-1487, https://doi.org/10.1016/j.tiv.2006.05.001
  - González, N.V., Soloneski, S., Larramendy, M. L. 2007. The chlorophenoxy herbicide dicamba and its commercial formulation banvel® induce genotoxicity and cytotoxicity in Chinese hamster ovary (CHO) cells. Mutation Research/Genetic Toxicology and Environmental Mutagenesis. 634(1–2): 60-68. https://doi.org/10.1016/j.mrgentox.2007.06.001
  - Perocco, P. et al. 1990. Evaluation of genotoxic effects of the herbicide dicamba using in vivo and in vitro test systems. Environmental and Molecular Mutagenesis. 15(3): 131-135. https://onlinelibrary.wiley.com/doi/abs/10.1002/em.2850150303
- **Developmental/birth defects:**
  - Weselak, M. et al. 2008. Pre- and post-conception pesticide exposure and the risk of birth defects in an Ontario farm population. Reproductive Toxicology. 25(4): 472-480. https://www.sciencedirect.com/science/article/abs/pii/S0890623808001354
- **Liver/kidney**:
  - U.S. EPA. 2016. Dicamba and Dicamba BAPMA Salt: Human-Health Risk Assessment for Proposed Section 3 New Uses on Dicamba-tolerant Cotton and Soybean. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0223-0002
  - Espandiari, P. et al. 1995. The herbicide dicamba (2-Methoxy-3,6-dichlorobenzoic acid) is a peroxisome proliferator in rats. Toxicological Sciences. 26(1): 85–90. https://academic.oup.com/toxsci/article-abstract/26/1/85/1706373
- **Neurotoxic:**
  - U.S. EPA. 2016. Dicamba and Dicamba BAPMA Salt: Human-Health Risk Assessment for Proposed Section 3 New Uses on Dicamba-tolerant Cotton and Soybean. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0223-0002

- Potter, W.T., Garry, V.F., Kelly, J.T., Tarone, R., Griffith, J., Nelson, R.L. 1993. Radiometric assay of red cell and plasma cholinesterase in pesticide appliers from Minnesota. Toxicology and Applied Pharmacology. 119(1): 150-155. https://pubmed.ncbi.nlm.nih.gov/8470119/
- Beasley et al. 1991. A pilot study of 2,4-dichlorophenoxyacetic acid- and dicamba-induced myotonia in experimental dogs. Veterinary and Human Toxicology. 33(5): 435-440.

- **Irritant or sensitizer:**

  - U.S. EPA. 2016. Dicamba and Dicamba BAPMA Salt: Human-Health Risk Assessment for Proposed Section 3 New Uses on Dicamba-tolerant Cotton and Soybean. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0223-0002

2,4-D

- **Cancer**

  - International Agency for Research on Cancer. 2015. IARC Monographs Evaluate DDT, Lindane, and 2,4-D. World Health Organization: Geneva, Switzerland. https://www.iarc.who.int/wp-content/uploads/2018/07/pr236_E.pdf
  - Smith, A. M., Smith, M. T., La Merrill, M. A., Liaw, J., & Steinmaus, C. 2017. 2,4-dichlorophenoxyacetic acid (2,4-D) and risk of non-Hodgkin lymphoma: a meta-analysis accounting for exposure levels. Annals of Epidemiology. 27(4): 281–289. https://doi.org/10.1016/j.annepidem.2017.03.003

- **Genotoxic:**

  - Mesnage, R. et al. 2021. Genotoxicity evaluation of 2,4-D, dicamba and glyphosate alone or in combination with cell reporter assays for DNA damage, oxidative stress and unfolded protein response. Food and Chemical Toxicology. 157: 112601. https://doi.org/10.1016/j.fct.2021.112601
  - Maire, M. A., Rast, C., Landkocz, Y., & Vasseur, P. 2007. 2,4-Dichlorophenoxyacetic acid: effects on Syrian hamster embryo (SHE) cell transformation, c-Myc expression, DNA damage and apoptosis. Mutation Research. 631(2): 124–136. https://doi.org/10.1016/j.mrgentox.2007.03.008

- **Reproductive:**

  - U.S. EPA. 2005. 2,4-D. HED's Revised Human Health Risk Assessment for the Reregistration Eligibility Decision (RED) Revised to Reflect Public Comments. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2004-0167-0080
  - Ferris Pasquini, V., Hurtazo, H., Quintanilla, F., & Cruz-Soto, M. 2023. 2,4-Dichlorophenol shows estrogenic endocrine disruptor activity by altering male rat sexual behavior. Toxics. 11(10): 843. https://doi.org/10.3390/toxics11100843

- **Developmental/birth defects:**

  - Rappazzo, K.M., et al. 2019. Maternal residential exposure to specific agricultural pesticide active ingredients and birth defects in a 2003-2005 North Carolina birth cohort. Birth Defects Reseach. 111(6): 312-323. https://pubmed.ncbi.nlm.nih.gov/30592382/
  - Silver, M. K., Shao, J., Li, M., Ji, C., Chen, M., Xia, Y., Lozoff, B., & Meeker, J. D. 2019. Prenatal exposure to the herbicide 2,4-D is associated with deficits in auditory processing during infancy. Environmental Research. 172: 486–494. https://doi.org/10.1016/j.envres.2019.02.046
  - U.S. EPA. 2005. 2,4-D. HED's Revised Human Health Risk Assessment for the Reregistration Eligibility Decision (RED) Revised to Reflect Public Comments. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2004-0167-0080

- **Liver/kidney:**
  - U.S. EPA. 2005. 2,4-D. HED's Revised Human Health Risk Assessment for the Reregistration Eligibility Decision (RED) Revised to Reflect Public Comments. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2004-0167-0080

- **Neurotoxic**:
  - U.S. EPA. 2005. 2,4-D. HED's Revised Human Health Risk Assessment for the Reregistration Eligibility Decision (RED) Revised to Reflect Public Comments. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2004-0167-0080

- **Endocrine disruptor:**
  - U.S. EPA. 2005. 2,4-D. HED's Revised Human Health Risk Assessment for the Reregistration Eligibility Decision (RED) Revised to Reflect Public Comments. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2004-0167-0080
  - Ferris Pasquini, V., Hurtazo, H., Quintanilla, F., & Cruz-Soto, M. 2023. 2,4-Dichlorophenol shows estrogenic endocrine disruptor activity by altering male rat sexual behavior. Toxics. 11(10): 843. https://doi.org/10.3390/toxics11100843

- **Retinal Degeneration and Cataracts**:
  - U.S. EPA. 2005. 2,4-D. HED's Revised Human Health Risk Assessment for the Reregistration Eligibility Decision (RED) Revised to Reflect Public Comments. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2004-0167-0080

Atrazine

- **Cancer:**
  - Kettles et al. 1997. Triazine herbicide exposure and breast cancer incidence: An ecologic study of Kentucky counties. Environmental Health Perspectives. 105(11): 1222 - 1227. https://ehp.niehs.nih.gov/doi/10.1289/ehp.971051222
  - Fan et al. 2007. Atrazine-induced aromatase expression is SF-1 dependent: Implications for endocrine disruption in wildlife and reproductive cancers in humans. Environmental Health Perspectives. 115(5): 720-727. https://ehp.niehs.nih.gov/doi/10.1289/ehp.9758

- **Endocrine:**
  - Cooper et al. 2000. Atrazine disrupts the hypothalamic control of pituitary-ovarian function. Toxicological Sciences. 53(2): 297–307. https://doi.org/10.1093/toxsci/53.2.297
  - Eldridge, J. C., Wetzel, L. T., & Tyrey, L. 1999. Estrous cycle patterns of Sprague-Dawley rats during acute and chronic atrazine administration. Reproductive Toxicology. 13(6): 491–499. https://doi.org/10.1016/s0890-6238(99)00056-8
  - U.S. EPA. Atrazine. Draft Human Health Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2013-0266-1159

- **Reproductive:**
  - Fan et al. 2007. Atrazine-induced aromatase expression is SF-1 dependent: Implications for endocrine disruption in wildlife and reproductive cancers in humans. Environmental Health Perspectives. 115(5): 720-727. https://ehp.niehs.nih.gov/doi/10.1289/ehp.9758
  - Cooper et al. 2000. Atrazine disrupts the hypothalamic control of pituitary-ovarian function. Toxicological Sciences. 53(2): 297–307. https://doi.org/10.1093/toxsci/53.2.297

- Chevrier et al. 2011. Urinary biomarkers of prenatal atrazine exposure and adverse birth outcomes in the PELAGIE birth cohort. Environmental Health Perspectives. 119(7): 1034-1041. https://ehp.niehs.nih.gov/doi/full/10.1289/ehp.1002775
- Almberg, K. S., Turyk, M. E., Jones, R. M., Rankin, K., Freels, S., & Stayner, L. T. 2018. Atrazine contamination of drinking water and adverse birth outcomes in community water systems with elevated atrazine in Ohio, 20062008. International Journal of Environmental Research and Public Health. 15(9): 1889. https://doi.org/10.3390/ijerph15091889
- U.S. EPA. Atrazine. Draft Human Health Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2013-0266-1159

- **Liver/Kidney:**
  - U.S. EPA. Atrazine. Draft Human Health Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2013-0266-1159

- **Developmental:**
  - Lin et al. 2014. Gestational and lactational exposure to atrazine via the drinking water causes specific behavioral deficits and selectively alters monoaminergic systems in C57BL/6 mouse dams, juvenile and adult Offspring. Toxicological Sciences. 141(1): 90–102, https://doi.org/10.1093/toxsci/kfu107
  - U.S. EPA. Atrazine. Draft Human Health Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2013-0266-1159

- **Neurotoxic:**
  - Lin et al. 2014. Gestational and lactational exposure to atrazine via the drinking water causes specific behavioral deficits and selectively alters monoaminergic systems in C57BL/6 mouse dams, juvenile and adult Offspring. Toxicological Sciences. 141(1): 90–102, https://doi.org/10.1093/toxsci/kfu107
  - U.S. EPA. Atrazine. Draft Human Health Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2013-0266-1159

- **Cardiac:**
  - U.S. EPA. Atrazine. Draft Human Health Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2013-0266-1159

- **Immunotoxicity:**
  - U.S. EPA. Atrazine. Draft Human Health Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2013-0266-1159

Acetochlor

- **Cancer:**
  - Lerro, C. C. et al. 2015. Use of acetochlor and cancer incidence in the Agricultural Health Study. International Journal of Cancer. 137(5): 1167-1175. https://onlinelibrary.wiley.com/doi/abs/10.1002/ijc.29416
  - U.S. EPA. 2020. Acetochlor. Human Health Draft Risk Assessment to Support Registration Review. U.S. Environmental Protection Agency. https://downloads.regulations.gov/EPA-HQ-OPP-2016-0298-0019/content.pdf

- **Neurotoxic:**
  - U.S. EPA. 2020. Acetochlor. Human Health Draft Risk Assessment to Support Registration Review. U.S. Environmental Protection Agency. https://downloads.regulations.gov/EPA-HQ-OPP-2016-0298-0019/content.pdf

- **Endocrine:**
  - U.S. EPA. 2020. Acetochlor. Human Health Draft Risk Assessment to Support Registration Review. U.S. Environmental Protection Agency. https://downloads.regulations.gov/EPA-HQ-OPP-2016-0298-0019/content.pdf
  - Rollerova, E., Wsolova, L., & Urbancikova, M. 2014. Herbicide acetochlor interferes with proliferation activity of MCF-7 cells enhanced by estradiol. Endocrine Regulations. 48: 195–200. https://www.sav.sk/journals/uploads/02201641ER_48(4)_2014_195_Rollerova.pdf
  - Rollerova, E., Gasparova, Z., Wsolova, L., & Urbancikova, M. 2000. Interaction of acetochlor with estrogen receptor in the rat uterus. Acetochlor– possible endocrine modulator? General Physiology and Biophysics. 19: 73-84.

- **Cytotoxic:**
  - Song et al. 2019. Study on systemic and reproductive toxicity of acetochlor in male mice. Toxicology Research. 8(1): 77–89, https://doi.org/10.1039/c8tx00178b
  - Huang, T. et al. 2020. Toxicity assessment of the herbicide acetochlor in the human liver carcinoma (HepG2) cell line. Chemosphere. 243: 125345. https://doi.org/10.1016/j.chemosphere.2019.125345

- **Reproductive:**
  - Song et al. 2019. Study on systemic and reproductive toxicity of acetochlor in male mice. Toxicology Research. 8(1): 77–89, https://doi.org/10.1039/c8tx00178b
  - U.S. EPA. 2020. Acetochlor. Human Health Draft Risk Assessment to Support Registration Review. U.S. Environmental Protection Agency. https://downloads.regulations.gov/EPA-HQ-OPP-2016-0298-0019/content.pdf

- **Liver/Kidney:**
  - Song et al. 2019. Study on systemic and reproductive toxicity of acetochlor in male mice. Toxicology Research. 8(1): 77–89, https://doi.org/10.1039/c8tx00178b
  - Shah, P.V. & Moretto, A. 2015. Acetochlor. Joint FAO/WHO Meeting on Pesticide Residues in Food (JMPR) Publications. World Health Organization: Geneva, Switzerland. January. https://apps.who.int/pesticide-residues-jmpr-database/Document/239
  - U.S. EPA. 2020. Acetochlor. Human Health Draft Risk Assessment to Support Registration Review. U.S. Environmental Protection Agency. https://downloads.regulations.gov/EPA-HQ-OPP-2016-0298-0019/content.pdf

- **Irritant/Sensitizer:**
  - U.S. EPA. 2020. Acetochlor. Human Health Draft Risk Assessment to Support Registration Review. U.S. Environmental Protection Agency. https://downloads.regulations.gov/EPA-HQ-OPP-2016-0298-0019/content.pdf
  - Shah, P.V. & Moretto, A. 2015. Acetochlor. Joint FAO/WHO Meeting on Pesticide Residues in Food (JMPR) Publications. World Health Organization: Geneva, Switzerland. January. https://apps.who.int/pesticide-residues-jmpr-database/Document/239

- **GI impacts:**
  - U.S. EPA. 2020. Acetochlor. Human Health Draft Risk Assessment to Support Registration Review. U.S. Environmental Protection Agency. https://downloads.regulations.gov/EPA-HQ-OPP-2016-0298-0019/content.pdf

- Shah, P.V. & Moretto, A. 2015. Acetochlor. Joint FAO/WHO Meeting on Pesticide Residues in Food (JMPR) Publications. World Health Organization: Geneva, Switzerland. January. https://apps.who.int/pesticide-residues-jmpr-database/Document/239

S-Metolachlor & Metolachlor

- **Cancer:**
  - Silver et al. 2015. Cancer incidence and metolachlor use in the Agricultural Health Study: An update. International Journal of Cancer. 137(11): 2630-2643. https://onlinelibrary.wiley.com/doi/abs/10.1002/ijc.29621
- **Cytotoxic**:
  - Roloff, B., Belluck, D., & Meisner, L. 1992. Cytogenetic effects of cyanazine and metolachlor on human lymphocytes exposed in vitro. Mutation Research. 281(4): 295–298. https://doi.org/10.1016/0165-7992(92)90024-c
- **Reproductive:**
  - Melo Tavares Vieira, K.C., et al. 2016. Maternal and fetal toxicity of Wistar rats exposed to herbicide metolachlor. Biological Sciences. 38(1): 91-98. https://www.redalyc.org/journal/1871/187146621012/html/
- **Developmental:**
  - Rappazzo, K.M., et al. 2019. Maternal residential exposure to specific agricultural pesticide active ingredients and birth defects in a 2003-2005 North Carolina birth cohort. Birth Defects Reseach. 111(6): 312-323. https://pubmed.ncbi.nlm.nih.gov/30592382/
  - California Department of Pesticide Regulation. 2024. Human Health Reference Levels for Metolachlor/S-Metolachlor and Degradates in Groundwater. California Department of Pesticide Regulation: Sacramento, CA. https://www.cdpr.ca.gov/docs/risk/rcd/metolachlor_groundwater.pdf
  - U.S. EPA. 1995. Metolachlor. U.S. Environmental Protection Agency: Washington, D.C. https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-108801_1-Apr-95.pdf
- **Liver/Kidney:**
  - California Department of Pesticide Regulation. 2024. Human Health Reference Levels for Metolachlor/S-Metolachlor and Degradates in Groundwater. California Department of Pesticide Regulation: Sacramento, CA. https://www.cdpr.ca.gov/docs/risk/rcd/metolachlor_groundwater.pdf
  - U.S. EPA. 1995. Metolachlor. U.S. Environmental Protection Agency: Washington, D.C. https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-108801_1-Apr-95.pdf
  - Melo Tavares Vieira, K.C., et al. 2016. Maternal and fetal toxicity of Wistar rats exposed to herbicide metolachlor. Biological Sciences. 38(1): 91-98. https://www.redalyc.org/journal/1871/187146621012/html/
- **Endocrine**:
  - Mathias, F. T., Romano, R. M., Sleiman, H. K., de Oliveira, C. A., & Romano, M. A. 2012. Herbicide metolachlor causes changes in reproductive endocrinology of male wistar rats. ISRN Toxicology. 130846. https://doi.org/10.5402/2012/130846
- **Sensitizer/Irritant:**
  - California Department of Pesticide Regulation. 2024. Human Health Reference Levels for Metolachlor/S-Metolachlor and Degradates in Groundwater. California Department of Pesticide Regulation: Sacramento, CA. https://www.cdpr.ca.gov/docs/risk/rcd/metolachlor_groundwater.pdf

6. Ecological risks associated with top herbicides in U.S. corn and soy production: Sources and citations

Glyphosate

- **Native plants**
  - U.S. EPA. 2018. Registration Review - Preliminary Ecological Risk Assessment for Glyphosate and its Salts. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2009-0361-0077
  - Sesin, V., Davy, C. M., Stevens, K. J., Hamp, R., & Freeland, J. R. 2021. Glyphosate toxicity to native nontarget macrophytes following three different routes of incidental exposure. Integrated Environmental Assessment and Management. 17(3): 597–613. https://doi.org/10.1002/ieam.4350
  - Florencia, F.M., Carolina, T., Enzo, B., Leonardo, G. 2017. Effects of the herbicide glyphosate on non-target plant native species from Chaco forest (Argentina). Ecotoxicology and Environmental Safety. 144: 360-368. https://doi.org/10.1016/j.ecoenv.2017.06.049
  - Olszyk, D., Pfleeger, T., Nash, M., and Plocher, M. 2024. Effects of simulated glyphosate drift to native prairie plants and canola-compatible Brassicaceae species of North Dakota, United States. Elsevier B.V. 182: 106692 https://assessments.epa.gov/risk/document/&deid%3D362550

- **Pollinators**
  - U.S. EPA. 2018. Registration Review - Preliminary Ecological Risk Assessment for Glyphosate and its Salts. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2009-0361-0077
  - Pesticide Action Network Europe. 2023. Glyphosate: Glyphosate-Based Herbicides & Their Impact on Bees' Health. Pesticide Action Network Europe: Brussels, Belgium. March.
  - Battisti, L. et al. 2021. Is glyphosate toxic to bees? A meta-analytical review. Science of The Total Environment. 767: 145397, https://doi.org/10.1016/j.scitotenv

- **Birds**
  - U.S. EPA. 2018. Registration Review - Preliminary Ecological Risk Assessment for Glyphosate and its Salts. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2009-0361-0077
  - Ruuskanen, S., Rainio, M.J., Uusitalo, M. et al. 2020. Effects of parental exposure to glyphosate-based herbicides on embryonic development and oxidative status: a long-term experiment in a bird model. Scientific Reports. 10: 6349. https://doi.org/10.1038/s41598-020-63365-1
  - Fréville, M., Estienne, A., Ramé, C., Lefort, G., Chahnamian, M., Staub, C., Venturi, E., Lemarchand, J., Maximin, E., Hondelatte, A., Zemb, O., Canlet, C., Guabiraba, R., Froment, P., & Dupont, J. 2022. Chronic dietary exposure to a glyphosate-based herbicide results in total or partial reversibility of plasma oxidative stress, cecal microbiota abundance and short-chain fatty acid composition in broiler hens. Frontiers in Physiology. 13: 974688. https://doi.org/10.3389/fphys.2022.974688

- **Fish/aquatic organisms**
  - U.S. EPA. 2018. Registration Review - Preliminary Ecological Risk Assessment for Glyphosate and its Salts. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2009-0361-0077

- Lopes, A. R., Moraes, J. S., & Martins, C. M. G. 2022. Effects of the herbicide glyphosate on fish from embryos to adults: a review addressing behavior patterns and mechanisms behind them. Aquatic Toxicology. 251:106281. https://doi.org/10.1016/j.aquatox.2022.106281
- Faria, M. et al. 2021. Glyphosate targets fish monoaminergic systems leading to oxidative stress and anxiety. Environment International. 146: 106253. https://doi.org/10.1016/j.envint.2020.106253.
- Brovini, E.M., Cardoso, S.J., Quadra, G.R. et al. 2021. Glyphosate concentrations in global freshwaters: are aquatic organisms at risk? Environmental Science and Pollution Research. 28: 60635-60648. https://doi.org/10.1007/s11356-021-14609-8
- Rzymski, P., Klimaszyk, P., Kubacki, T., & Poniedziałek, B. 2013. The effect of glyphosate-based herbicide on aquatic organisms—A case study. Limnological Review. 13(4): 215-220. https://doi.org/10.2478/limre-2013-0024
- Tresnakova, N., Stara, A., & Velisek, J. 2021. Effects of glyphosate and its metabolite AMPA on aquatic organisms. Applied Sciences. 11(19): 9004. https://doi.org/10.3390/app11199004

- **Mammals**

- U.S. EPA. 2018. Registration Review - Preliminary Ecological Risk Assessment for Glyphosate and its Salts. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2009-0361-0077

- **Amphibians**

- Wagner, N. et al. 2013.Questions concerning the potential impact of glyphosate-based herbicides on amphibians. Environmental Toxicology and Chemistry. 32(8): 1688-1700. https://doi.org/10.1002/etc.2268
- Herek, J.S., Vargas, L., Trindade, S.A.R. et al. 2020. Can environmental concentrations of glyphosate affect survival and cause malformation in amphibians? Effects from a glyphosate-based herbicide on Physalaemus cuvieri and P. gracilis (Anura: Leptodactylidae). Environmental Science and Pollution Research. 27: 22619–22630. https://doi.org/10.1007/s11356-020-08869-z
- Pompermaier, A., Alves, C., Chagas, F.B. et al. 2024. Effects of glyphosate based herbicide exposure in early developmental stages of Physalaemus gracilis. Scientific Reports. 14: 25652. https://doi.org/10.1038/s41598-024-76338-5

- **Soil organisms**

- El jaohur, M., et al. 2023. Glyphosate reduces the biodiversity of soil macrofauna and benefits exotic over native species in a tropical agroecosystem. Basic and Applied Ecology. 73: 18-26. https://doi.org/10.1016/j.baae.2023.10.001
- Lima e Silva, C., & Pelosi, C. 2024. Effects of glyphosate on earthworms: From fears to facts. Integrated Environmental Assessment and Management. 20(5): 1330-1336. https://doi.org/10.1002/ieam
- Druille, M., Cabello, M.N., Omacini, M., Golluscio R.A. 2013. Glyphosate reduces spore viability and root colonization of arbuscular mycorrhizal fungi. Applied Soil Ecology. 64: 99–103.
- Zaller, J. G., Heigl, F., Ruess, L. Grabmaier, A. 2014. Glyphosate herbicide affects belowground interactions between earthworms and symbiotic mycorrhizal fungi in a model ecosystem. Scientific Reports. 4: 5634
- Gaupp-Berghausen, M., Hofer, M., Rewald, B. and Zaller, J.G. 2015. Glyphosate-based herbicides reduce the activity and reproduction of earthworms and lead to increased soil nutrient concentrations. Scientific Reports. 5: 12886.

Dicamba

- **Native plants**
  - U.S. EPA. 2022. Dicamba: Draft Ecological Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. August. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0223-0028
  - Knuffman, L., Erndt-Pitcher, K., May, E. 2020. Drifting Towards Disaster. National Wildlife Federation: Reston, VA; Prairie Rivers Network: Champaign, IL; Xerces Society: Portland, OR. https://xerces.org/sites/default/files/publications/20-021.pdf

- **Pollinators**
  - U.S. EPA. 2022. Dicamba: Draft Ecological Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. August. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0223-0028
  - Knuffman, L., Erndt-Pitcher, K., May, E. 2020. Drifting Towards Disaster. National Wildlife Federation: Reston, VA; Prairie Rivers Network: Champaign, IL; Xerces Society: Portland, OR. https://xerces.org/sites/default/files/publications/20-021.pdf
  - Bohnenblust, E., Egan, J. F., Mortensen, D., & Tooker, J. 2013. Direct and indirect effects of the synthetic-auxin herbicide dicamba on two lepidopteran species. Environmental Entomology. 42(3): 586–594. https://doi.org/10.1603/EN13021

- **Birds**
  - U.S. EPA. 2022. Dicamba: Draft Ecological Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. August. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0223-0028
  - Durkin, P. & Bosch, S. 2004. Dicamba: Human Health and Ecological Risk Assessment– Final Report. Syracuse Environmental Research Associates, Inc: Fayetteville, NY; Syracuse Research Corporation: Syracuse, NY. November. https://www.fs.usda.gov/foresthealth/pesticide/pdfs/112404_dicamba.pdf

- **Fish/aquatic organisms**
  - Felisbino et al. 2023. Teratogenic effects of the dicamba herbicide in Zebrafish (Danio rerio) embryos. Environmental Pollution. 334: 122187. https://doi.org/10.1016/j.envpol.2023.122187
  - Korkmaz, N. 2024. Toxic and histopathological effects induced by exposure to the pesticide dicamba in carp Cyprinus carpio L. Environmental Science and Pollution Research. 31: 65790–65803. https://doi.org/10.1007/s11356-024-35674-9
  - Zhu, L. et al. 2014 Dicamba affects sex steroid hormone level and mRNA expression of related genes in adult rare minnow (Gobiocypris rarus) at environmentally relevant concentrations. Environmental Toxicology. 30(6): 693 - 703. https://doi.org/10.1002/tox.21947

- **Mammals**
  - U.S. EPA. 2022. Dicamba: Draft Ecological Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. August. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0223-0028
  - Durkin, P. & Bosch, S. 2004. Dicamba: Human Health and Ecological Risk Assessment– Final Report. Syracuse Environmental Research Associates, Inc: Fayetteville, NY; Syracuse Research Corporation: Syracuse, NY. November. https://www.fs.usda.gov/foresthealth/pesticide/pdfs/112404_dicamba.pdf

- **Amphibians**
  - Attademo, A.M., Lajmanovich, R.C., Peltzer, P.M. et al. 2021. Effects of the emulsifiable herbicide Dicamba on amphibian tadpoles: an underestimated toxicity risk?. Environ Science and Pollution Research. 28: 31962–31974. https://doi.org/10.1007/s11356-021-13000-x

2,4-D

- **Native plants**
  - U.S. EPA. 2005. 2,4-D RED Facts. U.S. Environmental Protection Agency: Washington, D.C. June. https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-030001_30-Jun-05.pdf
  - Triques, M.C., et al. 2021. Assessing single effects of sugarcane pesticides fipronil and 2,4-D on plants and soil organisms. Ecotoxicology and Environmental Safety. 208: 111622. https://doi.org/10.1016/j.ecoenv.2020.111622
  - Boutin, C. et al. 2014. Herbicide impact on non-target plant reproduction: What are the toxicological and ecological implications? Environmental Pollution. 185: 295-306. https://doi.org/10.1016/j.envpol.2013.10.009.

- **Pollinators and insects:**
  - Freydier, L., Lundgren, J.G. 2016. Unintended effects of the herbicides 2,4-D and dicamba on lady beetles. Ecotoxicology. 25: 1270–1277. https://doi.org/10.1007/s10646-016-1680-4
  - Morton, H.L., Moffett, J.O. 1972. Ovicidal and larvicidal effects of certain herbicides on honey bees. Environmental Entomology. 1(5): 611–614. https://doi.org/10.1093/ee/1.5.611
  - USDA Forest Service. 2006. 2,4-D Human Health and Ecological Risk Assessment: FINAL REPORT. U.S. Department of Agriculture, Forest Service: Washington, D.C. September. https://www.fs.usda.gov/foresthealth/pesticide/pdfs/093006_24d.pdf

- **Birds**:
  - U.S. EPA. 2005. 2,4-D RED Facts. U.S. Environmental Protection Agency: Washington, D.C. June. https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-030001_30-Jun-05.pdf
  - Da Silva, A. P., Morais, E. R., Oliveira, E. C., & Ghisi, N. C. 2022. Does exposure to environmental 2,4-dichlorophenoxyacetic acid concentrations increase mortality rate in animals? A meta-analytic review. Environmental Pollution. 303: 119179. https://doi.org/10.1016/j.envpol.2022.119179
  - USDA Forest Service. 2006. 2,4-D Human Health and Ecological Risk Assessment: FINAL REPORT. U.S. Department of Agriculture, Forest Service: Washington, D.C. September. https://www.fs.usda.gov/foresthealth/pesticide/pdfs/093006_24d.pdf

- **Fish & aquatic organisms in its ester forms**
  - U.S. EPA. 2005. 2,4-D RED Facts. U.S. Environmental Protection Agency: Washington, D.C. June. https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-030001_30-Jun-05.pdf
  - Da Silva, A. P., Morais, E. R., Oliveira, E. C., & Ghisi, N. C. 2022. Does exposure to environmental 2,4-dichlorophenoxyacetic acid concentrations increase mortality rate in animals? A meta-analytic review. Environmental Pollution. 303: 119179. https://doi.org/10.1016/j.envpol.2022.119179
  - U.S.D.A. Forest Service. 2006. 2,4-D Human Health and Ecological Risk Assessment: FINAL REPORT. U.S. Department of Agriculture, Forest Service: Washington, D.C. September. https://www.fs.usda.gov/foresthealth/pesticide/pdfs/093006_24d.pdf

- **Mammals**
  - U.S. EPA. 2005. 2,4-D RED Facts. U.S. Environmental Protection Agency: Washington, D.C. June. https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-030001_30-Jun-05.pdf

- **Soil invertebrates**
  - Triques, M.C., et al. 2021. Assessing single effects of sugarcane pesticides fipronil and 2,4-D on plants and soil organisms. Ecotoxicology and Environmental Safety. 208: 111622. https://doi.org/10.1016/j.ecoenv.2020.111622

- USDA Forest Service. 2006. 2,4-D Human Health and Ecological Risk Assessment: FINAL REPORT. U.S. Department of Agriculture, Forest Service: Washington, D.C. September. https://www.fs.usda.gov/foresthealth/pesticide/pdfs/093006_24d.pdf

Atrazine

- **Native plants**
  - U.S. EPA. 2016. Refined Ecological Risk Assessment for Atrazine. U.S. Environmental Protection Agency: Washington, D.C. April. https://www.regulations.gov/document/EPA-HQ-OPP-2013-0266-0315
- **Pollinators & insects:**
  - U.S. EPA. 2016. Refined Ecological Risk Assessment for Atrazine. U.S. Environmental Protection Agency: Washington, D.C. April. https://www.regulations.gov/document/EPA-HQ-OPP-2013-0266-0315
  - Wang, K. et al. 2023. Atrazine exposure can dysregulate the immune system and increase the susceptibility against pathogens in honeybees in a dose-dependent manner. Journal of Hazardous Materials. 452: 131179. https://doi.org/10.1016/j.jhazmat.2023.131179
  - Helmer, S.H., Kerbaol, A., Aras, P. et al. 2015. Effects of realistic doses of atrazine, metolachlor, and glyphosate on lipid peroxidation and diet-derived antioxidants in caged honey bees (Apis mellifera). Environmental Science and Pollution Research. 22: 8010–8021. https://doi.org/10.1007/s11356-014-2879-7
- **Birds**
  - U.S. EPA. 2016. Refined Ecological Risk Assessment for Atrazine. U.S. Environmental Protection Agency: Washington, D.C. April. https://www.regulations.gov/document/EPA-HQ-OPP-2013-0266-0315
- **Fish & aquatic organisms:**
  - U.S. EPA. 2016. Refined Ecological Risk Assessment for Atrazine. U.S. Environmental Protection Agency: Washington, D.C. April. https://www.regulations.gov/document/EPA-HQ-OPP-2013-0266-0315
  - Fan et al. 2007. Atrazine-induced aromatase expression is SF-1 dependent: Implications for endocrine disruption in wildlife and reproductive cancers in humans. Environmental Health Perspectives. 115(5): 720-727. https://ehp.niehs.nih.gov/doi/10.1289/ehp.9758
  - Rohr, J.R., & McCoy, K.A. 2009. A qualitative meta-analysis reveals consistent effects of atrazine on freshwater fish and amphibians. Environmental Health Perspectives. 118(1): 20-32.
  - Santos, T.G., & Martinez, C.B.R. 2012. Atrazine promotes biochemical changes and DNA damage in a Neotropical fish species. Chemosphere. 89(9): 1118-1125. https://doi.org/10.1016/j.chemosphere.2012.05.096
- **Mammals**:
  - U.S. EPA. 2016. Refined Ecological Risk Assessment for Atrazine. U.S. Environmental Protection Agency: Washington, D.C. April. https://www.regulations.gov/document/EPA-HQ-OPP-2013-0266-0315
- **Amphibians**:
  - U.S. EPA. 2016. Refined Ecological Risk Assessment for Atrazine. U.S. Environmental Protection Agency: Washington, D.C. April. https://www.regulations.gov/document/EPA-HQ-OPP-2013-0266-0315
  - Fan et al. 2007. Atrazine-induced aromatase expression is SF-1 dependent: Implications for endocrine disruption in wildlife and reproductive cancers in humans. Environmental Health Perspectives. 115(5): 720-727. https://ehp.niehs.nih.gov/doi/10.1289/ehp.9758

- Rohr, J.R., & McCoy, K.A. 2009. A qualitative meta-analysis reveals consistent effects of atrazine on freshwater fish and amphibians. Environmental Health Perspectives. 118(1): 20-32.
- Hayes, T.B. et al. 2010. Atrazine induces complete feminization and chemical castration in male African clawed frogs (Xenopus laevis). Proceedings of the National Academy of Science U.S.A. 107(10): 4612-4617. https://doi.org/10.1073/pnas.0909519107

Acetochlor

- **Native plants**
  - U.S. EPA. 2020. Acetochlor: Draft Ecological Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. March. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0298-0021
- **Pollinators & insects:**
  - U.S. EPA. 2020. Acetochlor: Draft Ecological Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. March. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0298-0021
- **Birds**
  - U.S. EPA. 2020. Acetochlor: Draft Ecological Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. March. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0298-0021
  - Arshad, N., Alam, S., Rafay, M., Jabeen, G., Hussain, K., Hussain, R., Ullah, M. I., Iqbal, M., Fouad, D., & Ataya, F. S. 2024. Effects of environmental relevant concentrations of acetochlor on growth, hematology, serum biochemistry and histopathology of Japanese quail. PloS One. 19(9): e0306583. https://doi.org/10.1371/journal.pone.0306583
- **Fish & aquatic organisms**
  - U.S. EPA. 2020. Acetochlor: Draft Ecological Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. March. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0298-0021
  - Lu, A. et al. A comparative review and computational assessment of acetochlor toxicity in fish: A novel endocrine disruptor? Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology. 271: 109685. https://doi.org/10.1016/j.cbpc.2023.109685.
  - Huang, T., et al. 2021. Exposure to acetochlor impairs swim bladder formation, induces heat shock protein expression, and promotes locomotor activity in zebrafish (Danio rerio) larvae. Ecotoxicology and Environmental Safety. 228: 112978. https://doi.org/10.1016/j.ecoenv.2021.112978
  - Li, W. et al. 2009. Effects of exposure to acetochlor on the expression of thyroid hormone related genes in larval and adult rare minnow (Gobiocypris rarus). Aquatic Toxicology. 94(2): 87-93. https://doi.org/10.1016/j.aquatox.2009.06.002
- **Mammals**
  - U.S. EPA. 2020. Acetochlor: Draft Ecological Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. March. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0298-0021
- **Soil organisms**
  - Zhang, J., Liang, W., Wu, X. et al. 2013. Toxic effects of acetochlor on mortality, reproduction and growth of Caenorhabditis elegans and Pristionchus pacificus. Bulletin of Environmental Contamination and Toxicology. 90: 364–368. https://doi.org/10.1007/s00128-012-0915-1

S-Metolachlor & Metolachlor

- **Native plants**
  - U.S. EPA. 1995. R.E.D. Facts: Metolachlor. U.S. Environmental Protection Agency: Washington, D.C. https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-108801_1-Apr-95.pdf

- **Pollinators**
  - Helmer, S.H., Kerbaol, A., Aras, P. et al. 2015. Effects of realistic doses of atrazine, metolachlor, and glyphosate on lipid peroxidation and diet-derived antioxidants in caged honey bees (Apis mellifera). Environmental Science and Pollution Research. 22: 8010–8021. https://doi.org/10.1007/s11356-014-2879-7
  - Main, A.R. 2020. Wild pollinators are exposed to a range of pesticides while foraging in agroecosystems. Science of The Total Environment. 742: 140436. https://doi.org/10.1016/j.scitotenv.2020.140436
  - Graham, K.K., Milbrath, M.O., Zhang, Y. et al. 2021. Identities, concentrations, and sources of pesticide exposure in pollen collected by managed bees during blueberry pollination. Scientific Reports. 11: 16857. https://doi.org/10.1038/s41598-021-96249-z

- **Birds**
  - U.S. EPA. 1995. R.E.D. Facts: Metolachlor. U.S. Environmental Protection Agency: Washington, D.C. https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-108801_1-Apr-95.pdf

- **Fish & aquatic organisms**
  - U.S. EPA. 1995. R.E.D. Facts: Metolachlor. U.S. Environmental Protection Agency: Washington, D.C. https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-108801_1-Apr-95.pdf

- **Mammals**
  - U.S. EPA. 1995. R.E.D. Facts: Metolachlor. U.S. Environmental Protection Agency: Washington, D.C. https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-108801_1-Apr-95.pdf

REFERENCES

1 Owens, T., Leslie, G. 2024. Summary: Regenerative Ag CPG Targets: Mapping the landscape of corporate engagement. CREO Syndicate: Burnaby, Canada.

2 Newton, P., Civita, N., Frankel-Goldwater, L., Bartel, K., Johns, C. 2020. What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes. Frontiers in Sustainable Food Systems. 4. https://www.researchgate.net/publication/346409644_What_Is_Regenerative_Agriculture_A_Review_of_Scholar_and_Practitioner_Definitions_Based_on_Processes_and_Outcomes

3 Tyson, J. R. 2022.Tyson foods leads $152M effort to support adoption of sustainable agriculture practices as part of USDA program. The Feed. September 16. Online. https://thefeed.blog/2022/09/16/tyson-foods-leads-152m-effort-to-support-adoption-of-sustainable-agriculture-practices-as-part-of-usda-program%EF%BF%BC/

4 ADM. 2024. ADM Regenerative Agriculture Brochure. ADM: Chicago, IL. https://www.adm.com/globalassets/standalone-pages/regenerative-agriculture/adm-regenerative-agriculture-brochure-eng-global-24.pdf

5 Cargill. Implement conservation tillage, reduced tillage, or No-Till farming. Cargill: Wayzata, MN. Webpage. Accessed February 10, 2025. https://www.cargill.com/sustainability/implement-conservation-tillage-reduced-tillage-or-no-till-farm

6 USDA. 2022. Census of Agriculture Highlights - Farm and Farmland. https://www.nass.usda.gov/Publications/Highlights/2024/Census22_HL_FarmsFarmland.pdf

7 USDA. 2022. NASS Highlights, 2021 Agriculture Chemical Use Survey: Corn. U.S. Department of Agriculture: Washington, D.C. May. https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/2021_Field_Crops/chemhighlights-corn.pdf.

8 USDA. 2024. NASS Highlights, 2023 Agriculture Chemical Use Survey: Soybeans. U.S. Department of Agriculture: Washington, D.C. May. https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/2023_Barley_Oats_Peanuts_Soybeans/ChemHighlights-Soybeans-2023.pdf.

9 Puglisi, E. 2012. Response of microbial organisms (aquatic and terrestrial) to pesticides. EFSA Supporting Publications. 9(11), 359E.

10 Gunstone, T., Cornelisse, T., Klein, K., Dubey, A., Donley, N. 2021. Pesticides and soil invertebrates: A hazard assessment. Frontiers in Environmental Science. 9. https://www.frontiersin.org/articles/10.3389/fenvs.2021.643847

11 Newton, P., Civita, N., Frankel-Goldwater, L., Bartel, K., Johns, C. 2020. What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes. Frontiers in Sustainable Food Systems. 4. https://www.researchgate.net/publication/346409644_What_Is_Regenerative_Agriculture_A_Review_of_Scholar_and_Practitioner_Definitions_Based_on_Processes_and_Outcomes

12 USDA. 2024. Climate-Smart Agriculture and Forestry (CSAF) Mitigation and Activities List for FY2024. U.S. Department of Agriculture: Washington, D.C. https://www.nrcs.usda.gov/sites/default/files/2024-01/ND%20CSAF%20Mitigation%20Activities_FY%2024%20List%20UPDATED%20JAN%202024.pdf

13 Bayer. Enhanced Bayer Carbon Program Offers Growers New Opportunities in 2021 and Beyond. Bayer AG: Leverkusen, Germany. Webpage. Accessed July 18, 2024. https://www.bayer.com/en/us/enhanced-carbon-program

14 Kelloway, C., Davidson, J.. 2023. Agricultural Carbon Markets, Payments, and Data: Big Ag's Latest Power Grab. Friends of the Earth: Washington, D.C. and Open Markets Institute: Washington, D.C. March. https://foe.org/wp-content/uploads/2023/02/Carbon-Markets-Report_Final_Updated.pdf

15 For Ground by Bayer. Bayer Carbon Program. Bayer AG: Leverkusen, Germany. Webpage. Accessed January 7, 2025. https://bayerforground.com/carbon-initiative

16 Syngenta. Regenerative Agriculture. Syngenta Group: Basel, Switzerland. Webpage. Accessed July 18, 2024. https://www.syngentagroup.com/regenerative-agriculture#what-is-regenerative-agriculture

17 Cook, Christopher, K. Hamerschlag, and K. Klein. 2016. Farming for the Future: Organic and Agroecological Solutions to Feed the World. https://foe.org/resources/farm-for-future-organic-solutions/

18 Lal, R., Reicosky, D.C., Hanson, J.D. 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil and Tillage Research. 93(1): 1-12. https://www.sciencedirect.com/science/article/abs/pii/S0167198706002522

19 DeJong-Hughes, J., Daigh, A. Tillage Implements. University of Minnesota Extension: St. Paul, MN. Webpage. Accessed July 18, 2024. https://extension.umn.edu/soil-management-and-health/tillage-implements-purpose-and-ideal-use#deep-tillage-%28deeper-than-10-inches%29-1202761

20 Ibid.

21 Lal, R., Reicosky, D.C., Hanson, J.D. 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil and Tillage Research. 93(1): 1-12. https://www.sciencedirect.com/science/article/abs/pii/S0167198706002522

22 Schonbeck, M., Jerkins, D., Ory, J. 2017. Soil Health and Organic Farming: Practical Conservation Tillage. Organic Farming Research Foundation: Santa Cruz, CA. https://ofrf.org/wp-content/uploads/2019/09/Tillage_Report_V6-F_WebRes-150.pdf

23 Delonge, M., Stillerman, K. P. 2020. Eroding the Future. Union of Concerned Scientists: Cambridge, MA. https://www.ucsusa.org/sites/default/files/2021-02/eroding-the-future-dec-2020.pdf

24 USDA Economic Research Service. Adoption of Conservation Tillage Has Increased Over the Past Two Decades on Acreage Planted to Major U.S. Cash Crops. United States Department of Agriculture: Washington, D.C. Webpage. Accessed July 18, 2024. https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=105042#:~:text=On%20wheat%20acres%2C%20no%2Dtill,from%2028%20percent%20in%202016

25 USDA Natural Resources Conservation Service. 2022. Reduction in Annual Fuel Use from Conservation Tillage. United States Department of Agriculture: Washington, D.C. November. https://www.nrcs.usda.gov/sites/default/files/2022-11/CEAP-Croplands-2022-ConservationInsight-FuelSavingswithConservationTillage.pdf

26 Hood, A.E.M., Jameson, H.R., and Cotterell, R. 1963. DESTRUCTION OF PASTURES BY PARAQUAT AS A SUBSTITUTE FOR PLOUGHING. Nature. 197: 748. https://www.nature.com/articles/197748a0.pdf

27 Hood, A. E. M. 1965. Ploughless farming using 'GRAMAXONE.' Outlook on Agriculture. 4(6), 286-294. https://journals.sagepub.com/doi/abs/10.1177/003072706500400604

28 Lessiter, M. 2022. No-till's herbicide history. No-Till Farmer. March 30. Online. https://www.no-tillfarmer.com/articles/11363-no-tills-herbicide-history-part-i

29 Derpsch, R., Friedrich, T., Kassam, A., & Li, H. 2010. Current status of adoption of no-till farming in the world and some of its main benefits. International Journal of Agricultural and Biological Engineering. 3(1): 1-25.

30 Huggins, D. R., & Reganold, J. P. 2008. No-till: the quiet revolution. Scientific American. 299 (1), 70-77.

31 Pittelkow, C. M., Linquist, B. A., Lundy, M. E., Liang, X., Van Groenigen, K. J., Lee, J., ... & Van Kessel, C. 2015. When does no-till yield more? A global meta-analysis. Field Crops Research. 183: 156-168.

32 Kelloway, C., Davidson, J.. 2023. Agricultural Carbon Markets, Payments, and Data: Big Ag's Latest Power Grab. Friends of the Earth: Washington, D.C. and Open Markets Institute: Washington, D.C. March. https://foe.org/wp-content/uploads/2023/02/Carbon-Markets-Report_Final_Updated.pdf

33 Bayer. Regenerative Agriculture at Bayer. Bayer AG: Leverkusen, Germany. Webpage. Accessed July 18, 2024. https://www.bayer.com/en/agriculture/regenerative-agriculture-definition

34 Syngenta. Regenerative Agriculture. Syngenta Group: Basel, Switzerland. Webpage. Accessed July 18, 2024. https://www.syngentagroup.com/regenerative-agriculture#what-is-regenerative-agriculture

35 Bayer. Enhanced Bayer Carbon Program Offers Growers New Opportunities in 2021 and Beyond. Bayer AG: Leverkusen, Germany. Webpage. Accessed July 18, 2024. https://www.bayer.com/en/us/enhanced-carbon-program

36 Delate, K. Cambardella, C.,Chase, C., Turnbull, R.. 2015. A review of long-term organic comparison trials in the U.S.. Sustainable Agriculture Research. 4.

37 Tautges, N. E., Chiartas, J. L., Gaudin, A. C., O'Geen, A. T., Herrera, I., & Scow, K. M. 2019. Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils. Global Change Biology. 25 (11): 3753-3766.

38 Diacono, M., Montemurro, F. 2011. Long-term effects of organic amendments on soil fertility. Sustainable Agriculture. 2: 761-786.

39 Mancinelli, R., Campiglia, E., Di Tizio, A., & Marinari, S. 2010. Soil carbon dioxide emission and carbon content as affected by conventional and organic cropping systems in Mediterranean environment. Applied Soil Ecology. 46(1): 64-72.

40 Nannipieri, P., Ascher, J., Ceccherini, M.T., Landi, L., Pietramellara, G., Renella, G. 2003. Microbial diversity and soil functions. European Journal of Soil Science. 54: 655–670. https://flore.unifi.it/handle/2158/663759

41 USDA. 2022. NASS Highlights, 2021 Agriculture Chemical Use Survey: Corn. U.S. Department of Agriculture: Washington, D.C. May. https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/2021_Field_Crops/chemhighlights-corn.pdf. See Methodology.

42 USDA. 2024. NASS Highlights, 2023 Agriculture Chemical Use Survey: Soybeans. U.S. Department of Agriculture: Washington, D.C. May. https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/2023_Barley_Oats_Peanuts_Soybeans/ChemHighlights-Soybeans-2023.pdf. See Methodology.

43 Huggins, D. R., & Reganold, J. P. 2008. No-till: The quiet revolution. Scientific American. 299 (1), 70-77.

44 Friedrich, T. 2005. Does no-till farming require more herbicides?. Outlooks on Pest Management. 16 (4): 188.

45 Pittelkow, C. M., Linquist, B. A., Lundy, M. E., Liang, X., Van Groenigen, K. J., Lee, J., ... & Van Kessel, C. 2015. When does no-till yield more? A global meta-analysis. Field Crops Research. 183: 156-168.

46 Hristovska, T.; Watkins, K.B.; Anders, M.M. 2013. An economic risk analysis of no-till management for the rice-soybean rotation system used in Arkansas. Journal of Soil and Water Conservation. 68: 132–137.

47 USDA Natural Resources Conservation Service. 2016. PRACTICE STANDARD RESIDUE AND TILLAGE MANAGEMENT, NO TILL: Code 329. U.S. Department of Agriculture: Washington, D.C. https://www.nrcs.usda.gov/sites/default/files/2022-09/Residue_And_Tillage_Management_No_Till_329_CPS_0.pdf

48 Khalil, Y., Flower, K., Siddique K. H. M., Ward P. 2018. Effect of crop residues on interception and activity of prosulfocarb, pyroxasulfone, and trifluralin. PLoS One. 2018. 6;13(12): e0208274. https://pmc.ncbi.nlm.nih.gov/articles/PMC6283640/

49 Banks, P.A., Robinson, E.L. 2017. Soil Reception and activity of acetochlor, alachlor, and metolachlor as affected by wheat (Triticum aestivum) straw and Irrigation. Weed Science. 34(4): 607-611.

50 Ghadiri, H., Shea, P.J., Wicks, G.A. 2017. Interception and retention of atrazine by wheat (Triticum aestivum L.) stubble. Weed Science. 32(1): 24-27.

51 Result obtained from the Pesticide Use Data System (PUDS), based on USDA QuikStat surveys and NASS data for corn and soy. See Appendix

52 Result obtained from the Pesticide Use Data System (PUDS), based on USDA QuikStat surveys and NASS data for corn and soy. See Appendix

53 Result obtained from the Pesticide Use Data System (PUDS), based on USDA QuikStat surveys and NASS data for corn and soy. See Appendix

54 Tangamornsuksan, W., Lohitnavy, O., Sruamsiri, R., Chaiyakunapruk, N., Norman Scholfield, C., Reisfeld, B., & Lohitnavy, M. (2019). Paraquat exposure and Parkinson's disease: A systematic review and meta-analysis. Archives of Environmental & Occupational Health, 74(5), 225-238.

55 Result obtained from the Pesticide Use Data System (PUDS), based on USDA QuikStat surveys and NASS data for corn and soy. See Appendix

56 Heap, I. 2014. Global perspective of herbicide-resistant weeds. Pest Management Science. 70: 1306–1315. https://pubmed.ncbi.nlm.nih.gov/24302673/

57 Varah, A., Ahodo, K., Coutts, S. R., Hicks, H. L., Comont, D., Crook, L., Hull, R., Neve, P., Childs, D. Z., Freckleton R. P., Norris, K. 2020. The costs of human-induced evolution in an agricultural system. Nature Sustainability. 3(1): 63-71.

58 USDA Economic Research Service. Ag and Food Sectors and the Economy. U.S. Department of Agriculture: Washington, D.C. Webpage. Accessed July 18, 2024. https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/ag-and-food-sectors-and-the-economy

59 Bonny, S. 2016. Genetically modified herbicide-tolerant crops, weeds, and herbicides: Overview and impact. Environmental Management. 57(1): 31-48. https://pubmed.ncbi.nlm.nih.gov/26296738/

60 USDA Economic Research Service. Adoption of Genetically Engineered Crops in the U.S.. U.S. Department of Agriculture: Washington, D.C. Webpage. Accessed July 18, 2024. See Methodology.

61 Result obtained from the Pesticide Use Data System (PUDS), based on USDA QuikStat surveys and NASS data for corn and soy. See Appendix.

62 Pesticide Action Network International. 2021. PAN International List of Highly Hazardous Pesticides. Pesticide Action Network International: Hamburg, Germany. March. https://pan-international.org/wp-content/uploads/PAN_HHP_List.pdf

63 Marquez, E.C, Schafer, K.S. 2016. Kids on the Frontline: How Pesticides Are Undermining the Health of Rural Children. Pesticide Action Network: Berkeley, CA. https://www.panna.org/wp-content/uploads/2016/04/KOF-report-final.pdf

64 Farmworker Justice. 2013. Exposed and Ignored. Farmworker Justice: Washington, D.C. https://www.farmworkerjustice.org/wp-content/uploads/2013/07/Exposed-and-Ignored-by-Farmworker-Justice-email-version.pdf

65 Knuffman, L., Erndt-Pitcher, K., May, E. 2020. Drifting Towards Disaster. National Wildlife Federation: Reston, VA; Prairie Rivers Network: Champaign, IL; Xerces Society: Portland, OR. https://xerces.org/sites/default/files/publications/20-021.pdf

66 U.S. EPA. 2022. Dicamba: Draft Ecological Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0223-0028

67 U.S. EPA. 2020. Acetochlor: Draft Ecological Risk Assessment for Registration Review. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0298-0021

68 Simon, G. 2023. Glyphosate-Based Herbicides and Their Impact on Bees' Health. Pesticide Action Network Europe: Brussels, Belgium. https://www.pan-europe.info/sites/pan-europe.info/files/public/resources/briefings/Glyphosate%20based%20herbicides%20and%20their%20impact%20on%20bees%27%20health.pdf

69 USDA. The Importance of Pollinators. U.S. Department of Agriculture: Washington, D.C. Webpage. Accessed October 18, 2024. https://www.usda.gov/peoples-garden/pollinators

70 U.S. EPA. 2016. Refined Ecological Risk Assessment for Atrazine. U.S. Environmental Protection Agency: Washington, D.C. https://www.regulations.gov/document/EPA-HQ-OPP-2016-0298-0021

71 Douglas, M. R., & Tooker, J. F. 2015. Large-scale deployment of seed treatments has driven rapid increase in use of neonicotinoid insecticides and preemptive pest management in US field crops. Environmental Science & Technology. 49(8): 5088-5097.

72 US Geological Survey Pesticide National Synthesis Project. Estimated Annual Agricultural Pesticide Use. U.S Geological Survey: Reston, VA. Webpage. Accessed July 18, 2024. https://water.usgs.gov/nawqa/pnsp/usage/maps/. (Note: the data we use is from 2014, the most recent year that USGS collected neonicotinoid seed data.)

73 US Geological Survey. Online. Estimated Annual Agricultural Pesticide Use. https://water.usgs.gov/nawqa/pnsp/usage/maps/

74 Sánchez-Bayo, F., & Wyckhuys, K. A. 2019. Worldwide decline of the entomofauna: A review of its drivers. Biological conservation. 232: 8-27.

75 Strouhova, A., Velisek, J., & Stara, A. 2023. Selected neonicotinoids and associated risk for aquatic organisms. Veterinární Medicína. 68(8): 313.

76 DiBartolomeis, M., Kegley, S., Mineau, P., Radford, R., & Klein, K. 2019. An assessment of acute insecticide toxicity loading (AITL) of chemical pesticides used on agricultural land in the United States. PloS one. 14(8): e0220029.

77 Li, Y., Miao, R., & Khanna, M. 2020. Neonicotinoids and decline in bird biodiversity in the United States. Nature Sustainability. 3(12): 1027-1035.

78 U.S. EPA Office of Pesticide Programs. 2023. Imidacloprid, Thiamethoxam and Clothianidin: Draft Predictions of Likelihood of Jeopardy and Adverse Modification for Federally Listed Endangered and Threatened Species and Designated Critical Habitats. U.S. Environmental Protection Agency. May. https://www.epa.gov/system/files/documents/2023-05/ESA-JAM-Analysis.pdf

79 U.S. EPA. 2014. Memorandum: Benefits of Neonicotinoid Seed Treatments to Soybean Production. U.S Environmental Protection Agency: Washington, D.C. October. https://www.epa.gov/sites/default/files/2014-10/documents/benefits_of_neonicotinoid_seed_treatments_to_soybean_production_2.pdf

80 Gurian-Sherman, Doug. 2017. Alternative to Neonicotinoid Insecticide Coated Corn Seeds. Prepared for Center for Food Safety. https://www.centerforfoodsafety.org/files/alternatives-to-neonics_v9_23186.pdf

81 Krupke, C.H., Holland, J.D., Long, E.Y., Eitzer, B.D. 2017. Planting of neonicotinoid-treated maize poses risks for honey bees and other non-target organisms over a wide area without consistent crop yield benefit. Journal of Applied Ecology. 54: 1449-1458. https://besjournals.onlinelibrary.wiley.com/doi/full/10.1111/1365-2664.12924

82 Douglas, M.R. and Tooker, J.F. 2015. Large-scale deployment of seed treatments has driven rapid increase in use of neonicotinoid insecticides and preemptive pest management in U.S. field crops. Environmental Science & Technology. 49: 8, 5088–5097. https://pubs.acs.org/doi/abs/10.1021/es506141g

83 Held, L. 2024. Why farmers use harmful insecticides they may not need. Civil Eats. October 30. Online. https://civileats.com/2024/10/30/why-farmers-use-harmful-insecticides-they-may-not-need/

84 Cimino, A.M., Boyles, A.L., Thayer, K.A., Perry M.J. 2017. Effects of neonicotinoid pesticide exposure on human health: A systematic review. Environmental Health Perspectives. 125 (2):155-162. https://pmc.ncbi.nlm.nih.gov/articles/PMC5289916/

85 Benchikh, I., Ziani, K., Gonzalez Mateos, A., Khaled, B. M. 2024. Non-acute exposure of neonicotinoids, health risk assessment, and evidence integration: A systematic review. Critical Reviews in Toxicology. 54(3): 194–213. https://www.tandfonline.com/doi/full/10.1080/10408444.2024.2310593

86 Mikolić, A., & Karačonji, I. B. 2018. Imidacloprid as reproductive toxicant and endocrine disruptor: investigations in laboratory animals. Archives of Industrial Hygiene and Toxicology. 69(2): 103-108.

87 Zhang, J. J., Yi, W., Xiang, H. Y., Li, M. X., Li, W. H., Wand, X. Z., & Zhang, J. H. 2011. Oxidative stress: role in acetamiprid-induced impairment of the male mice reproductive system. Agricultural Sciences in China. 10(5): 786-796.

88 USDA. 2022. NASS Highlights, 2021 Agriculture Chemical Use Survey: Corn. U.S. Department of Agriculture: Washington, D.C. May. https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/2021_Field_Crops/chemhighlights-corn.pdf

89 U.S. EPA. Dead Zones and Harmful Algal Blooms. U.S. Environmental Protection Agency: Washington, D.C. Webpage. Accessed January 10, 2025. https://www.epa.gov/nutrientpollution/effects-dead-zones-and-harmful-algal-blooms

90 Ward, M. H., Jones, R. R., Brender, J. D., De Kok, T. M., Weyer, P. J., Nolan, B. T., Villanueva, C. M., & Van Breda, S. G. 2018. Drinking water nitrate and human health: An updated review. International Journal of Environmental Research and Public Health. 15(7): 1557. https://www.mdpi.com/1660-4601/15/7/1557

91 USDA. 2024. NASS Highlights, 2023 Agriculture Chemical Use Survey: Soybeans. U.S. Department of Agriculture: Washington, D.C. May. https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/2023_Barley_Oats_Peanuts_Soybeans/ChemHighlights-Soybeans-2023.pdf. See Methodology.

92 Smith, P. E. T. E., Powlson, D. S., Glendining, M. J., & Smith, J. U. 1998. Preliminary estimates of the potential for carbon mitigation in European soils through no‐till farming. Global Change Biology. 4(6): 679-685.

93 USDA Natural Resources Conservation Service. 2016. Reduction in Annual Fuel Use from Conservation Tillage. U.S. Department of Agriculture; Washington, D.C. August. https://www.nrcs.usda.gov/publications/ceap-crop-2016-reduction-in-annual-fuel-use-from-conservation-tillage.pdf

94 Jackson, L. E., Santos-Martin, F., Hollander, A. D., Horwath, W. R., Howitt, R. E., Kramer, J. B., ... & Sumner, D. A. 2009. Potential for adaptation to climate change in an agricultural landscape in the Central Valley of California. California Climate Change Center. 165.

95 Puglisi, E. 2012. Response of microbial organisms (aquatic and terrestrial) to pesticides. EFSA Supporting Publications. 9(11), 359E.

96 Gunstone, T., Cornelisse, T., Klein, K., Dubey, A., & Donley, N. 2021. Pesticides and soil invertebrates: A hazard assessment. Frontiers in Environmental Science. 9: 643847.

97 Pesticide Action Network. 2023. Pesticides and Climate Change: A Vicious Cycle. Pesticide Action Network: Berkeley, CA. https://www.panna.org/wp-content/uploads/2023/02/202308ClimateChangeEng.pdf

98 Ziesemer, Jodi. 2007. Energy Use in Organic Food Systems. Food and Agriculture Organization of the United Nations: Rome. http://www.fbae.org/2009/FBAE/website/images/pdf/imporatant-publication/fao-organic-report.pdf

99 Jian, J., Du, X., Reiter, M.S., Stewart, R. D. 2020. A meta-analysis of global cropland soil carbon changes due to cover cropping. Soil Biology and Biochemistry. 143: 107735 https://www.sciencedirect.com/science/article/abs/pii/S0038071720300328

100 Bolinder, M.A., Crotty, F., Elsen, A. et al. 2020. The effect of crop residues, cover crops, manures and nitrogen fertilization on soil organic carbon changes in agroecosystems: A synthesis of reviews. Mitigation and Adaptation Strategies for Global Climate Change. 25: 929–952. https://link.springer.com/article/10.1007/s11027-020-09916-3

101 Fargione, J.E. et al. 2018. Natural climate solutions for the United States. Science Advances. 4 (11). https://www.science.org/doi/full/10.1126/sciadv.aat1869

102 USDA. 2024. Climate-Smart Agriculture and Forestry (CSAF) Mitigation and Activities List for FY2024. U.S. Department of Agriculture: Washington, D.C. https://www.nrcs.usda.gov/sites/default/files/2024-01/ND%20CSAF%20Mitigation%20Activities_FY%2024%20List%20UPDATED%20JAN%202024.pdf

103 Audsley, E., Stacey, K., Parsons, D.J., Williams, A.G., 2009. Estimation of the Greenhouse Gas Emissions from Agricultural Pesticide Manufacture and Use. Bedford, UK: Cranfield University.

104 U.S. EPA. Greenhouse Gas Emissions from a Typical Passenger Vehicle. U.S. EPA: Washington, D.C. Webpage. Accessed July 24, 2024. https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle

105 Audsley, E., Stacey, K., Parsons, D.J., Williams, A.G., 2009. Estimation of the Greenhouse Gas Emissions from Agricultural Pesticide Manufacture and Use. Bedford, UK: Cranfield University.

106 Menegat, S., Ledo, A. & Tirado, R. 2022. Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture. Scientific Reports. 12: 14490. See Table 1. https://www.nature.com/articles/s41598-022-18773-w

107 U.S. EPA. Understanding Global Warming Potentials. U.S. EPA: Washington, D.C. Webpage. Accessed July 24, 2024. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

108 U.S. EPA. 2023. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021. EPA 430-R-23-002. U.S. Environmental Protection Agency: Washington, D.C. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions andsinks-1990-2021

109 See Appendix 4: Methodology.

110 Biardeau, L., Crebbin-Coates, R., Keerati, R., Litke, S., Rodriguez, H. 2016. Soil Health and Carbon Sequestration in USCroplands: A Policy Analysis. Prepared for the USDA Natural Resources Conservation Service (NRCS) and the Berkeley Food Institute (BFI). Goldman School of Public Policy, University of California – Berkeley: Berkeley, CA. May. https://food.berkeley.edu/wp-content/uploads/2016/05/GSPPCarbon_03052016_FINAL.pdf

111 Slessarev, E., Zelikova, J., Hamman, J., Cullenward, D., and Freeman, J. 2021. Depth matters for soil carbon accounting. CarbonPlan. Online. Accessed July 24, 2024. https://carbonplan.org/research/soil-depth-sampling

112 Baker, J. M., Ochsner, T. E., Venterea, R. T., Griffis, T. J. 2007. Tillage and soil carbon sequestration: What do we really know? Agriculture, Ecosystems & Environment. 118(1-4): 1-5.

113 Luo, Z., Wang, E., Sun, O.J. 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agriculture, Ecosystems & Environment. 139 (1-2): 224-231. https://www.sciencedirect.com/science/article/abs/pii/S0167880910002094

114 Du, Z., Angers, D. A., Ren, T., Zhang, Q., & Li, G. (2017). The effect of no-till on organic C storage in Chinese soils should not be overemphasized: A meta-analysis. Agriculture, Ecosystems & Environment, 236, 1-11.

115 CarbonPlan (online). Depth Matters for Soil Carbon Accounting. https://carbonplan.org/research/soil-depth-sampling

116 Ogle, S. M., Swan, A., Paustian, K. 2012. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agriculture, Ecosystems & Environment. 149: 37-49.

117 Claassen, R., Bowman, M., McFadden, J., Smith, D., Wallander, S. 2018. Tillage Intensity and Conservation Cropping in the United States. U.S. Department of Agriculture: Washington, D.C. September. https://www.ers.usda.gov/webdocs/publications/90201/eib197_summary.pdf?v=1377.3

118 Conant, R. T., Easter, M., Paustian, K., Swan, A., Williams, S. 2007. Impacts of periodic tillage on soil C stocks: A synthesis. Soil and Tillage Research, 95 (1–2), 1-10. https://www.sciencedirect.com/science/article/abs/pii/S0167198707000050

119 Ogle, S.M., Alsaker, C., Baldock, J. et al. 2019. Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. Scientific Reports. 9: 11665. https://doi.org/10.1038/s41598-019-47861-7

120 Luo, Z., Wang, E., Sun, O.J. 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agriculture, Ecosystems & Environment. 139 (1-2): 224-231. https://www.sciencedirect.com/science/article/abs/pii/S0167880910002094

121 Pelster, et al. 2021. Reduced tillage increased growing season N2O emissions from a fine but not a coarse textured soil under the cool, humid climate of eastern Canada. Soil and Tillage Research, 206, 104833

122 Hassan, et al. 2022. Management strategies to mitigate N2O emissions in agriculture. Life, 12(3), 439.

123 Gunstone, T., Cornelisse, T., Klein, K., Dubey, A., Donley, N. 2021. Pesticides and soil invertebrates: A hazard assessment. Frontiers in Environmental Science. 9. https://www.frontiersin.org/articles/10.3389/fenvs.2021.643847

124 Puglisi, E. 2012. Response of microbial organisms (aquatic and terrestrial) to pesticides. EFSA Supporting Publications. 9(11): 359E.

125 Vahter, T., Sepp, S.-K., Astover, A., Helm, A., Kikas, T., Liu, S., Oja, J., Öpik, M., Penu, P., Vasar, M., Veromann, E., Zobel, M., & Hiiesalu, I. 2022. Landscapes, management practices and their interactions shape soil fungal diversity in arable fields: Evidence from a nationwide farmers' network. Soil Biology and Biochemistry. 168: 108652. https://doi.org/10.1016/j.soilbio.2022.108652

126 Walder, F., Schmid, M. W., Riedo, J., Valzano-Held, A. Y., Banerjee, S., Büchi, L., Bucheli, T. D., & van der Heijden, M. G. A. 2022.. Soil microbiome signatures are associated with pesticide residues in arable landscapes. Soil Biology and Biochemistry. 174. 108830. https://doi.org/10.1016/j.soilbio.2022.108830

127 Ibid.

128 Strom, S. 2013. Misgivings About How a Weed Killer Affects the Soil. The New York Times. September 19. Online. https://www.nytimes.com/2013/09/20/business/misgivings-about-how-a-weed-killer-affects-the-soil.html

129 The Soil Association. The Impact of Glyphosate on Soil Health: The Evidence to Date. The Soil Association: Bristol, England. https://www.soilassociation.org/media/7202/glyphosate-and-soil-health-full-report.pdf

130 Marks, S. 2019. Concerns over glyphosate pass from human health to the soil. Politico. April 9. Online. https://www.politico.eu/article/glyphosate-concerns-pass-from-human-health-to-soil/

131 Druille, M., Cabello, M.N., Omacini, M., Golluscio R.A. 2013. Glyphosate reduces spore viability and root colonization of arbuscular mycorrhizal fungi. Applied Soil Ecology. 64: 99–103.

132 Zaller, J. G., Heigl, F., Ruess, L. Grabmaier, A. 2014. Glyphosate herbicide affects belowground interactions between earthworms and symbiotic mycorrhizal fungi in a model ecosystem. Scientific Reports. 4: 5634.

133 Yamada, T., Kremer, R., Castro, P. and Wood, B. 2009. Glyphosate interactions with physiology, nutrition, and diseases of plants: Threat to sustainability. European Journal of Agronomy. 31(3): 111-113

134 Gaupp-Berghausen, M., Hofer, M., Rewald, B. and Zaller, J.G. 2015. Glyphosate-based herbicides reduce the activity and reproduction of earthworms and lead to increased soil nutrient concentrations. Scientific Reports. 5: 12886.

135 Dobberstein, J. 2017. Is Glyphosate Harming Your No-Tilled Soil? No-Till Farmer. October 28. Online. https://www.no-tillfarmer.com/articles/7169-is-glyphosate-harming-your-no-tilled-soils?v=preview

136 Tripathi, S., Srivastava, P., Devi, R. S., & Bhadouria, R. 2020. Influence of synthetic fertilizers and pesticides on soil health and soil microbiology. In Agrochemicals detection, treatment and remediation (pp. 25-54). Butterworth-Heinemann.

137 Pahalvi, H. N., Rafiya, L., Rashid, S., Nisar, B., & Kamili, A. N. 2021. Chemical fertilizers and their impact on soil health. Microbiota and Biofertilizers, Vol 2: Ecofriendly tools for reclamation of degraded soil environs, 1-20.

138 Williams, D. M., Blanco-Canqui, H., Francis, C. A., & Galusha, T. D. 2017. Organic farming and soil physical properties: an assessment after 40 years. Agronomy Journal. 10: 600-609.

139 Lotter, D., Seidel, R., Liebhardt, W. 2003. The performance of organic and conventional cropping systems in an extreme climate year. American Journal of Alternative Agriculture. 18(3): 146-154.

140 Pecenka, J.R., Ingwell, L.L., Foster, R.E., Krupke, C.H., Kaplan,I. 2021. IPM reduces insecticide applications by 95% while maintaining or enhancing crop yields through wild pollinator conservation. Proceedings of the National Academy of Sciences, U.S.A. 118 (44): e2108429118. https://www.pnas.org/doi/10.1073/pnas.2108429118

141 Pretty, J., Bharucha, Z.P. 2015. Integrated Pest Management for sustainable intensification of agriculture in Asia and Africa. Insects. 6(1): 152-82. https://pmc.ncbi.nlm.nih.gov/articles/PMC4553536/

142 Venterea, R.T., Coulter J.A., Dolan, M.S. 2016. Evaluation of intensive "4R" strategies for decreasing nitrous oxide emissions and nitrogen surplus in rainfed corn. Journal of Environmental Quality. 45(4):1186-95. https://pubmed.ncbi.nlm.nih.gov/27380066/

143 Project Drawdown. Nutrient Management. Project Drawdown: St. Paul, MN. Webpage. Accessed January 10, 2025. https://drawdown.org/solutions/nutrient-management

144 USDA Economic Research Service. Fertilizer share of expected corn production expenses drops back after 2021–22 spike. U.S. Department of Agriculture: Washington, D.C. Webpage. Accessed January 7, 2025. https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=108828

145 USDA Economic Research Service. 2024 Farm Sector Income Forecast. U.S. Department of Agriculture: Washington, D.C. Webpage. Accessed January 7, 2025. https://www.ers.usda.gov/topics/farm-economy/farm-sector-income-finances/farm-sector-income-forecast/

146 LaCanne, C. E., & Lundgren, J. G. 2018. Regenerative agriculture: Merging farming and natural resource conservation profitably. PeerJ. 6: e4428.

147 Texas A&M AgriLife Extension Service. 2022. Integrated Pest Management (IPM) Program for Cotton. Texas A&M AgriLife Extension Service: College Station, TX. https://agrilifeextension.tamu.edu/wp-content/uploads/2023/09/Cotton-IPM-2022a.pdf

148 Lechenet, M., Dessaint, F., Py, G. et al. 2017. Reducing pesticide use while preserving crop productivity and profitability on arable farms. Nature Plants. 3: 17008 https://www.nature.com/articles/nplants20178

149 Dainese, M., Martin, E. A., Aizen, M. A., Albrecht, M., Bartomeus, I., Bommarco, R., … & Steffan-Dewenter, I. 2019. A global synthesis reveals biodiversity-mediated benefits for crop production. Science Advances. 5(10): eaax0121.

150 Friends of the Earth. 2024. Organic is Regenerative. Friends of the Earth: Washington, D.C. http://foe.org/wp-content/uploads/2025/01/Organic-is-Regenerative-Science-Brief-Final.pdf

151 Gattinger, A. et al. 2012. Enhanced top soil carbon stocks under organic farming. Proceedings of the National Academy of Sciences. 109(44): 18226-18231

152 Ghabbour, E.A. et al. 2017. National comparison of the total and sequestered organic matter contents of conventional and organic farm soils. Advances in Agronomy. 146: 1-35.

153 Niles, M. 2008. Sustainable soils: reducing, mitigating, and adapting to climate change with organic agriculture. Sustainable Development Law & Policy. 9: 19.

154 Cavigelli, M.A., Mirsky, S.B., Teasdale, J.R., Spargo, J.T., Doran, J.W. 2013. Organic management systems to enhance ecosystem services. Renewable Agriculture and Food Systems. 28: 145-159.

155 Martins, B., Cavigelli, M.A., Maul, J.E., Buyer, J.S., Le, A.N., Rasmann, C., Martin-Neto, L. 2014. Spectroscopic characterization and evaluation of SOM in areas under different soil tillage systems. 10th Meeting of the Brazilian Chapter of the International Humic Substances Society Conference (October 14-18, 2013, Santo Antonio de Goias, Goias State): 69-72.

156 Coulter, J., et al. 2013. Productivity, economics, and soil quality in the Minnesota variable-input cropping systems trial. Crop Management. 12.

157 Williams, D. M., Blanco-Canqui, H., Francis, C. A., & Galusha, T. D. 2017. Organic farming and soil physical properties: An assessment after 40 Years. Agronomy Journal. 10: 600-609.

158 Borron, S. 2006. Building Resilience for an Unpredictable Future: How Organic Agriculture Can Help Farmers Adapt to Climate Change. Food and Agriculture Organization of the United Nations: Rome, Italy.

159 Bengtsson, J., Ahnstrom, J. & Weibull, A. 2005. The effects of organic agriculture on biodiversity and abundance: a meta-analysis. Journal of Applied Ecology. 4: 261-269.

160 Lichtenberg, E. M., Kennedy, C. M., Kremen, C., Batary, P., Berendse, G., Bonmarco, R., Crowder, D. 2017. A global synthesis of the effects of diversified farming systems on arthropod diversity within fields and across agricultural landscapes. Global Change Biology. 23: 4946–4957.

161 Crowder, D. W., Northfield, T. D., Gomulkiewicz, R. & Snyder, W. E. 2012. Conserving and promoting evenness: organic farming and fire-based wildland management as case studies. Ecology. 93: 2001-2007

162 Friends of the Earth. Organic for All. Friends of the Earth: Washington, D.C. Webpage. Accessed January 7, 2025. www.organicforall.org

163 King, F.H. 1911. Farmers of Forty Centuries; or Permanent Agriculture in China, Korea and Japan (2004 edition). Dover Publications, Inc: Mineola, NY.

164 Schonbeck, M., Jerkins, D., Ory, J. 2017. Soil Health and Organic Farming: Practical Conservation Tillage. Organic Farming Research Foundation: Santa Cruz, CA. https://ofrf.org/wp-content/uploads/2019/09/Tillage_Report_V6-F_WebRes-150.pdf

165 Luo, Z., Wang, E., Sun, O. J. 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agriculture, Ecosystems & Environment. 139 (1-2): 224-231.

166 Organic Production and Handling Requirements, 7 CFR § 205.203 (2024). https://www.ecfr.gov/current/title-7/subtitle-B/chapter-I/subchapter-M/part-205/subpart-C

167 Delate, K. Cambardella, C.,Chase, C., Turnbull, R. 2015. A review of long-term organic comparison trials in the U.S. Sustainable Agriculture Research. 4.

168 Tautges, N. E., Chiartas, J. L., Gaudin, A. C., O'Geen, A. T., Herrera, I., & Scow, K. M. 2019. Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils. Global Change Biology. 25 (11): 3753-3766.

169 Diacono, M., Montemurro, F. 2011. Long-term effects of organic amendments on soil fertility. Sustainable Agriculture. 2: 761-786.

170 Mancinelli, R., Campiglia, E., Di Tizio, A., & Marinari, S. 2010. Soil carbon dioxide emission and carbon content as affected by conventional and organic cropping systems in Mediterranean environment. Applied Soil Ecology. 46(1): 64-72.

171 Seufert, V., Ramankutty, N. 2017. Many shades of gray: The context-dependent performance of organic agriculture. Science Advances. 3: e1602638.

172 Newton, P., Civita, N., Frankel-Goldwater, L., Bartel, K., Johns, C. 2020. What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes. Frontiers in Sustainable Food Systems. 4. https://www.researchgate.net/publication/346409644_What_Is_Regenerative_Agriculture_A_Review_of_Scholar_and_Practitioner_Definitions_Based_on_Processes_and_Outcomes

173 Frasconi, C., Martelloni, L., Antichi, D., Raffaeli, M., Fontanelli, M., Perruzi, A., Benincasa, P., Tosti, G. 2019. Combining roller crimpers and flaming for the termination of cover crops in herbicide-free no-till cropping systems. PLoS One.14(2): e0211573. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0211573, 6112436BCFB

174 Shirtliffe, S. J., Johnson, E. N. 2012. Progress towards no-till organic weed control in western Canada. Renewable Agriculture and Food Systems. 27(1): 60-67. https://www.cambridge.org/core/journals/renewable-agriculture-and-food-systems/article/abs/progress-towards-notill-organic-weed-control-in-western-canada/B37CA75A7FCB52034CF65

175 Dorn, B., Stadler, M., van der Heijden, M., Streit, B. 2013. Regulation of cover crops and weeds using a roll-chopper for herbicide reduction in no-tillage winter wheat. Soil and Tillage Research. 134: 121-132. https://www.sciencedirect.com/science/article/abs/pii/S0167198713001426

176 Nickel, R. 2024. Farmer saves $2 million in inputs with no-till system. Successful Farming. April 8. Online. https://www.agriculture.com/farmer-saves-usd2-million-in-inputs-with-no-till-system-8622367

177 Fargione, J. et al. 2008. Land clearing and the biofuel carbon debt. Science. 319: 1235-1238 https://www.science.org/doi/abs/10.1126/science.1152747

178 Searchinger, T. et al. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science. 319: 1238-1240. https://www.science.org/doi/abs/10.1126/science.1151861

179 Lark, T.J., Hendricks, N. P., Smith, A., Pates, N., Spawn-Lee, S. A., Bougie, M., Booth, E.G., Kucharik, C. J., Gibbs, H.K. 2022. Environmental outcomes of the US Renewable Fuel Standard, Proceedings of National Academy of Sciences U.S.A. 119 (9): e2101084119. https://www.pnas.org/doi/abs/10.1073/pnas.2101084119

180 Eisen, M.B., Brown, P.O. 2022. Rapid global phaseout of animal agriculture has the potential to stabilize greenhouse gas levels for 30 years and offset 68 percent of CO2 emissions this century. PLOS Climate. 1(2): e0000010. https://doi.org/10.1371/journal.pclm.0000010

181 Ivanovich, C.C., Sun, T., Gordon, D.R., Ocko, I.B. 2023. Future warming from global food consumption. Nature Climate Change. 13: 297–302. https://www.nature.com/articles/s41558-023-01605-8

182 Harwatt, H. 2019. Including animal to plant protein shifts in climate change mitigation policy: A proposed three-step strategy. Climate Policy. 19(5): 533–541. https://doi.org/10.1080/14693062.2018.1528965

183 Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. & Tempio, G. 2013. Tackling Climate Change Through Livestock – A Global Assessment of Emissions and Mitigation Opportunities. Food and Agriculture Organization of the United Nations: Rome, Italy. https://openknowledge.fao.org/server/api/core/bitstreams/492bb0b2-8b73-4e49-b188-8176b1d8c711/content

184 Foley, J. 2024. Regenerative grazing is over-hyped as a climate solution. We should do it anyway. Project Drawdown. August 15. Online. https://drawdown.org/insights/regenerative-grazing-is-overhyped-as-a-climate-solution-we-should-do-it-anyway

185 Resources such as the Pesticide Risk Tool may be helpful.

186 Natural Resources Conservation Service. 2022. Conservation Practice Standard 595: Pest Management Conservation System. U.S. Department of Agriculture: Washington, D.C. September. https://www.nrcs.usda.gov/sites/default/files/2022-09/Pest_Management_Conservation_System_595_CPS_10_2019.pdf

187 National Organic Coalition. Appropriations Priorities: Fiscal Year 2025 Requests. National Organic Coalition: Arlington, MA. https://app.box.com/s/hl9bvvpojo4jzck97ywxsr1wjf41kwjl

188 Resources such as the Pesticide Risk Tool may be helpful.