WORKING PAPERS

N° 1684

Octobre 2025

"Environmental Impacts of Genetically Modified Crops"

Frederik Noack, Dennis Engist, Josephine Gantois, Vasundhara Gaur, Batoule F Hyjazie, Ashley Larsen, Leithen K M'Gonigle, Anouch Missirian, Matin Qaim, Risa D Sargent, Eduardo Souza-Rodrigues, and Claire Kremen

Toulouse School of Economics

Environmental Impacts of Genetically Modified Crops

Frederik Noack[1], Dennis Engist[1*], Josephine Gantois[1,2*], Vasundhara Gaur[3*], Batoule F Hyjazie[4*], Ashley Larsen[5*], Leithen K M'Gonigle[6*], Anouch Missirian[7*], Matin Qaim[8,9*], Risa D Sargent[4*], Eduardo Souza-Rodrigues[10,11*], and Claire Kremen[2]

[1]Food and Resource Economics, University of British Columbia
[2]Institute for Resources, Environment and Sustainability, University of British Columbia
[3]Institute for Policy Integrity, New York University School of Law
[4]Land and Food Systems, University of British Columbia
[5]Bren School of Environmental Science & Management, University of California, Santa Barbara
[6]Department of Biological Sciences, Simon Fraser University
[7]Toulouse School of Economics, INRAe, University of Toulouse Capitole, Toulouse, France
[8]Center for Development Research (ZEF), University of Bonn, Germany
[9]Institute for Food and Resource Economics, University of Bonn, Germany
[10]Department of Economics, University of Toronto
[11]CEPR
[*]Alphabetical order, authors contributed equally

2024-06-11

Abstract

Genetically modified (GM) crops have been adopted by some of the world's leading agricultural nations, but the full extent of their environmental impacts remains largely unknown. While concerns about the direct environmental effects of GM crops have declined, GM crops have led to indirect changes in agricultural practices, including pesticide use, agricultural expansion, and cropping patterns with profound environmental implications. Recent studies paint a nuanced picture of these environmental impacts, with mixed effects of GM crop adoption on biodiversity, deforestation, and human health that vary with the GM trait and geographic scale. New GM or gene-edited crops with different traits would likely have different environmental and human health impacts.

Introduction

GM crops have been proposed as a solution to the dual challenge of meeting the demands of a growing global population while mitigating the environmental impacts of agriculture. By enhancing resistance to pests and other environmental stressors, GM traits have been promoted as having the potential to boost agricultural production without expanding agriculture into natural habitats or intensifying agrochemical applications (*1–3*).

While concerns about direct toxic effects of GM crops on non-target species and human health have attenuated recently (*4–6*), increasing evidence suggests that management changes arising from GM crop adoption, including shifts in pesticide use, the spread of monocultures, and local agricultural expansion, can have profound implications for human health and the environment (*7–9*).

Quantifying the positive and negative indirect effects of GM crop adoption on the environment and human health is challenging for several reasons. First, results from field trials are only partially helpful for understanding the real-world implications of GM crop adoption because they often hold other management factors constant and are thus uninformative about the broader environmental implications of these indirect management changes. Second, large-scale changes in agriculture, including the widespread adoption of GM crops, also affect non-adopting farmers through changes in crop prices and environmental spillovers. Examples of those spillovers include changes in pest population sizes (*10*), pesticide drift (*11*), the development of pesticide-resistant pest populations (*12*, *13*), and crop price effects (*14*, *15*) that incentivize agricultural expansion or contraction and changes in the use of agrochemicals elsewhere (*16–19*). Such spillovers also present a methodological challenge for isolating the causal effects of GM crop adoption on agricultural outcomes and the environment.

Recent advances in causal inference techniques hold promise for analyzing the real-world consequences of widespread GM crop adoption. Examples include the quantification of GM crop adoption impacts on health (*7*), deforestation (*8*), and biodiversity (*9*), although investigating spillovers and feedback through markets from large-scale adoption remains challenging.

Here, we summarize the literature on the environmental impacts of GM crop adoption and highlight pathways to fill remaining knowledge gaps. Our review primarily examines the impacts of GM crops that have already been widely adopted, but we conclude by discussing the potential effects of GM and gene-edited crops still in development. Also, we take as the counterfactual a world without GM crops but with an otherwise similar conventional production system.

Genetically modifying crop germplasm involves using modern biotechnological methods to achieve specific design objectives. The environmental effects of GM crops vary depending on their specific traits. While many traits have been developed to date, only two GM traits have been widely commercialized. These traits are herbicide tolerance (HT), which makes the crop tolerant to certain broad-spectrum herbicides, and insect resistance, where genes from the bacterium *Bacillus thuringiensis* (Bt) make the crop resistant to lepidopteran insect pests. These traits hold significant commercial value because farmers worldwide struggle with weeds and lepidopteran insect pests such as corn borers, armyworms, and bollworms (*20*).

Adopting these two GM traits can reduce crop losses by enhancing weed and pest control and consequently increase crop yields and profits. It can also affect the use of chemical pesticides and other management practices, which may further enhance yields and profitability. We discuss these direct and indirect environmental implications below.

GM Trait Development and Regulation

For nearly three decades, GM crop adoption has been limited to two main GM traits, HT and Bt, in four crops: soybean, corn, cotton, and canola. Since the initial approval of those traits for cultivation, many countries have introduced stricter and more expensive regulations for GM crop approval. As a result, many other GM traits developed in labs were rarely approved for commercial application (*21*), including traits for resistance to fungi and bacteria, tolerance to drought and heat, and improved nitrogen use efficiency (*22*). It is estimated that the cost of regulation for a single new GM trait is over

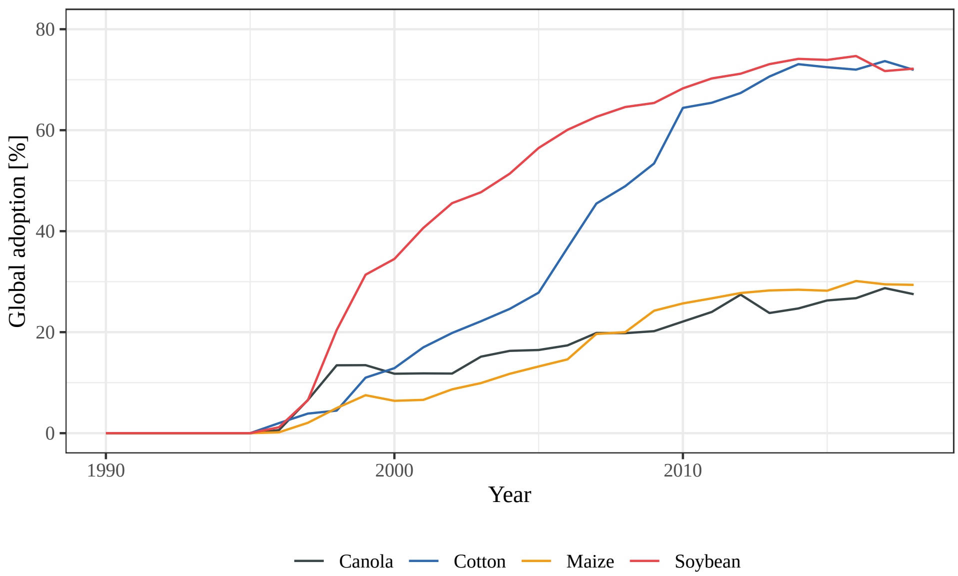

Figure 1: GM crop adoption over time. The percentage of global corn, cotton, soybean, and canola area under GM varieties. The data are from the status reports of the International Service for the Acquisition of Agri-biotech Applications (ISAAA) ((*34*) to (*35*)).

40 million US dollars for the trait developer (*23*). This regulatory cost is more than most public institutes and small and medium enterprises can afford (*24*), which not only prevents the commercialization of new GM traits but also contributes to a market dominated by a few large companies (*25–27*). These companies often patent their technologies and can inflate seed prices to raise their profits. While increased profits from technology development incentivize innovation by those companies, it simultaneously limits seed production by farmers and competing firms (*28*). The extent of market concentration is visible in the market for GM seeds. In 2020, four companies controlled over half of the world's seed market. These companies hold intellectual property rights to 95% of cotton and corn varieties and 84% of soybean varieties (*29*). In addition to regulatory hurdles and market concentration, growing consumer concerns about GM foods have prevented companies and countries from commercializing GM versions of typical food crops such as wheat and rice (*25*, *30*).

GM Crop Adoption

Once legally approved, farmers' decisions to adopt GM crops hinge on the expected profits of adoption and the associated risks (*31*), the availability of the technology and its alternatives, marketing exposure (*32*) and farm characteristics including farm size and farmer education level (*33*). Recent work demonstrates that herbicide drift that damages neighboring non-GM crops can further accelerate the adoption process (*11*).

Following their initial commercialization in 1996, GM varieties of corn, cotton, soybean, and canola saw swift adoption rates (Figure 1). By 2019, these GM varieties expanded to 190 million hectares,

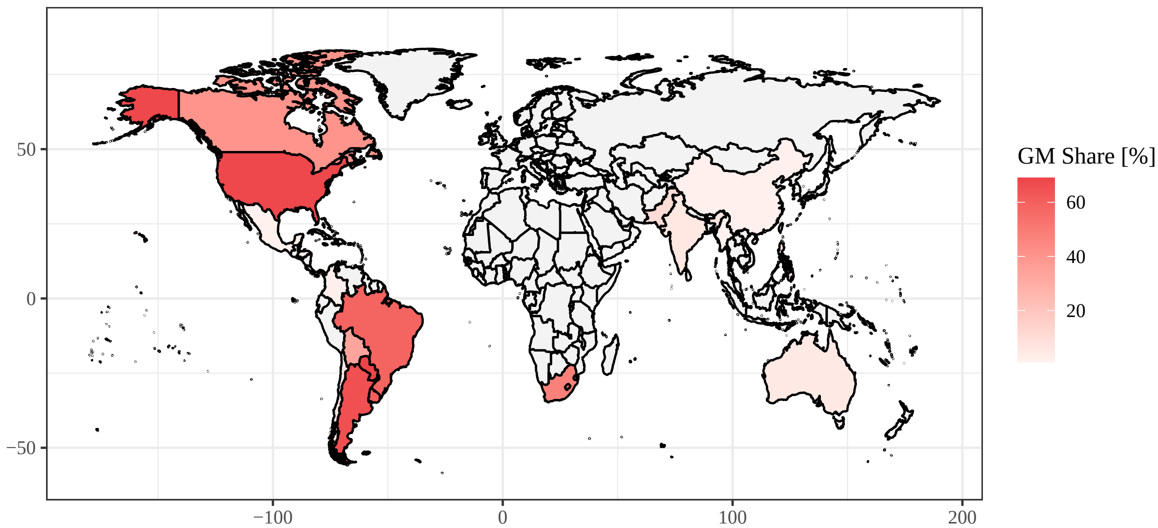

Figure 2: GM crop adoption across countries. Percentage of global corn, cotton, soybean, and canola cropland area planted with GM varieties. The data are from the status reports of the ISAAA ((*34*) to (*35*)).

representing 13% of global arable land, and were cultivated in 29 countries across various income levels (Figure 2). Among the 14 GM crops approved for cultivation, four crops dominate nearly 99% of the GM cultivation area, including GM soybeans (48.2% of the total GM area), GM corn (32%), cotton (13.5%), and canola (5.3%). While the HT trait is predominant in GM soybeans and canola, the Bt trait is common in GM cotton and corn, with some varieties in the USA and other nations featuring both, as 'stacked' traits (*35*).

More than half of the global GM crop area is concentrated in five countries: the USA (38% of the total global GM crop area), Brazil (28%), Argentina (13%), Canada (7%), and India (6%). Strict regulation prevents the adoption of GM crops in many non-adopting countries. An example of the impact of regulations occurred in Romania, which grew HT soybeans between 1999 and 2006 (with an adoption rate of 80% by the end of 2006) but had to suspend cultivation upon joining the European Union (EU) in 2007 (*36*).

While strong patent protection and high seed prices could limit GM crop adoption, they have not been major constraints. The main reason is that the protection of intellectual property rights is not uniform across countries. The International Convention for the Protection of New Varieties of Plants (UPOV, 1961) and the World Trade Organization's Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS, 1994) are the two main international agreements that govern intellectual property rights around innovation in plant and seed varieties. However, several countries are not signatories to the UPOV agreement and are therefore not required to apply its standards. Additionally, the TRIPS Agreement has provisions in Article 27(3)(b) that allow member nations to develop their own patents or other forms of protection (*37*, *38*). Consequently, in many low- and middle-income countries, GM crops are not patented, or patent protection is not strictly enforced when it exists. Once

GM crop technology receives approval in these countries, seed production and distribution face fewer legal barriers (*39*). This legal landscape contributes to lower seed prices in many low- and middle-income countries. Examples include Bt cotton in China, India, and Pakistan (*22*). In addition, some middle-income countries have begun developing generic GM varieties to facilitate small-scale farmers' access to GM crops. Notably, Indian universities have released three cost-effective, reusable Bt cotton varieties (*40*), and a public-private partnership in Bangladesh has successfully introduced a Bt eggplant variety embraced by small-scale farmers (*41*).

Quantifying the Causal Effects of GM Crops on Agricultural and Environmental Outcomes

Despite numerous studies analyzing the effects of GM crops on yields, pesticide use, and other outcomes, several challenges persist in accurately evaluating the impacts of this technology. Firstly, while experimental setups comparing GM crops with their non-GM counterparts can isolate the causal impact of GM technology on outcomes by holding all other inputs fixed, these may not reflect real-world outcomes. This discrepancy occurs because farmers who adopt GM crops might also alter other agricultural practices, such as pesticide and fertilizer use, which also affect agricultural and environmental outcomes (*14*).

Secondly, in more realistic, non-experimental settings, comparing outcomes between farmers (or countries) who adopt GM crops and those who do not can be confounded since adopters and non-adopters often differ in attributes such as farm size, education level, access to irrigation, and labor constraints (*33*), that can influence the outcomes of interest independently of GM crop adoption and related agricultural practices. Some of these differences can be accounted for with proper statistical techniques (e.g. Kathage and Qaim (*42*)). A global meta-analysis of the many existing studies with non-experimental farm-level data suggests that GM crop adoption contributes to significant yield gains, and that the Bt trait leads to reductions in chemical pesticide use, whereas the HT trait does not (*43*). However, challenges with causal inference persist because researchers can hardly observe all confounding characteristics that could potentially bias the estimates.

One approach to addressing these challenges is implementing randomized control trials (RCTs) in field settings, wherein randomly selected farmers receive incentives to adopt GM crops. These behavioral experiments enable farmers to modify their agricultural practices in conjunction with GM adoption, resulting in directly comparable groups of adopters and non-adopters. Ahmed et al. (*41*) conducted such an RCT in Bangladesh. The results of this study showed a 50% increase in yields and a 40% reduction in pesticide costs for Bt eggplant production compared to conventional eggplant production in the control villages.

Despite RCTs being the gold standard for causal inference, they are not without limitations. Firstly, the results from RCTs are not always scalable to larger, aggregated levels because market responses and spillovers are largely absent at the small scale of the experiments (*44*, *45*). Secondly, due to varying local conditions, these results may not be directly transferable to different settings, such as other countries or types of GM crops.

Causal inference techniques that evaluate the consequences of large-scale adoption across several countries are instrumental for understanding the real-world implications of GM crop adoption. A recent study by Hansen and Wingender (*46*) uses one such causal inference method to estimate the impact of

GM crop adoption on yields on a global scale. The study distinguished the effects of GM adoption from broader country-specific agricultural development by comparing yield differences across corn, cotton, soybean, and other crops before and after GM adoption across countries with and without GM crops, employing a triple difference methodology. They report no yield effects of GM soybean and rapeseed adoption but large and statistically significant yield effects of GM cotton and corn adoption. These results may overestimate the actual yield gains, however, because yield gains of such magnitude in some of the world's largest crop producers would change global crop prices and thus affect non-adopters' incentives for production. Indeed, Barrows et al. (*14*) found that GM crop adoption has reduced prices between 10% and 20% compared to the counterfactual world without GM crop adoption. While such a price reduction represents a benefit of GM crops for consumers, lower prices can diminish the revenues of non-adopting farmers, potentially prompting them to reduce land, fertilizer, and other inputs to agricultural production (*16–19*). To illustrate this methodological challenge, consider yield trends in adopting and non-adopting countries (Figure 3). Corn, cotton, and soybean yields were different in adopting and non-adopting countries even before the commercialization of GM crops and generally increased over time. Yields further diverged between adopting and non-adopting countries after the commercialization of GM crops, suggesting a positive impact of GM crops on yields (Figure 3). Causal inference approaches address the challenges arising from different yield levels before adoption and general time trends. However, if yield trends in non-adopting countries declined in response to GM commercialization due to, e.g., price effects, it would also contribute to the divergence of yields between adopting and non-adopting countries and thus lead to an overestimation of the positive yield effects of GM crops.

Agricultural Expansion and Deforestation

Yield increases from GM crop adoption may reduce the incentives to convert forests to croplands, thus reducing biodiversity loss and greenhouse gas emissions associated with land use change (*15*, *48*). The suggested mechanism for this land-sparing effect is that increased agricultural productivity through GM crop adoption leads to an increased harvest and, therefore, reduced crop prices, discouraging farmers from expanding their cropland into natural or semi-natural habitats. This general positive relationship between crop prices and deforestation, which drives the effect on agricultural expansion or contraction, has been established in various studies and locations (*18*, *49–51*) although unrelated to GM crops. Alternatively, increased profits from GM crop adoption, e.g., through reduced production costs or crop losses, could motivate farmers to expand agricultural production into natural habitats. For instance, Carreira et al. (*8*) find that deforestation in Brazil increased in areas with significant productivity gains from GM crop adoption compared to areas with low benefits of GM crop adoption, indicating a potential deforestation-inducing effect of GM crops.

While research specifically linking GM crop adoption to deforestation is limited, broader studies on agricultural productivity and deforestation present varied results (*52*, *53*). A possible explanation for these mixed results is that the contrasting outcomes may occur simultaneously but at different scales or in different locations. For example, while GM crop adoption might lead to agricultural expansion in adopting regions due to increased profits, it could simultaneously reduce agricultural expansion in non-adopting regions due to the lack of profitability gains in those regions and lower crop prices in response to the increased aggregate supply. Across all regions, this could lead to overall forest loss or

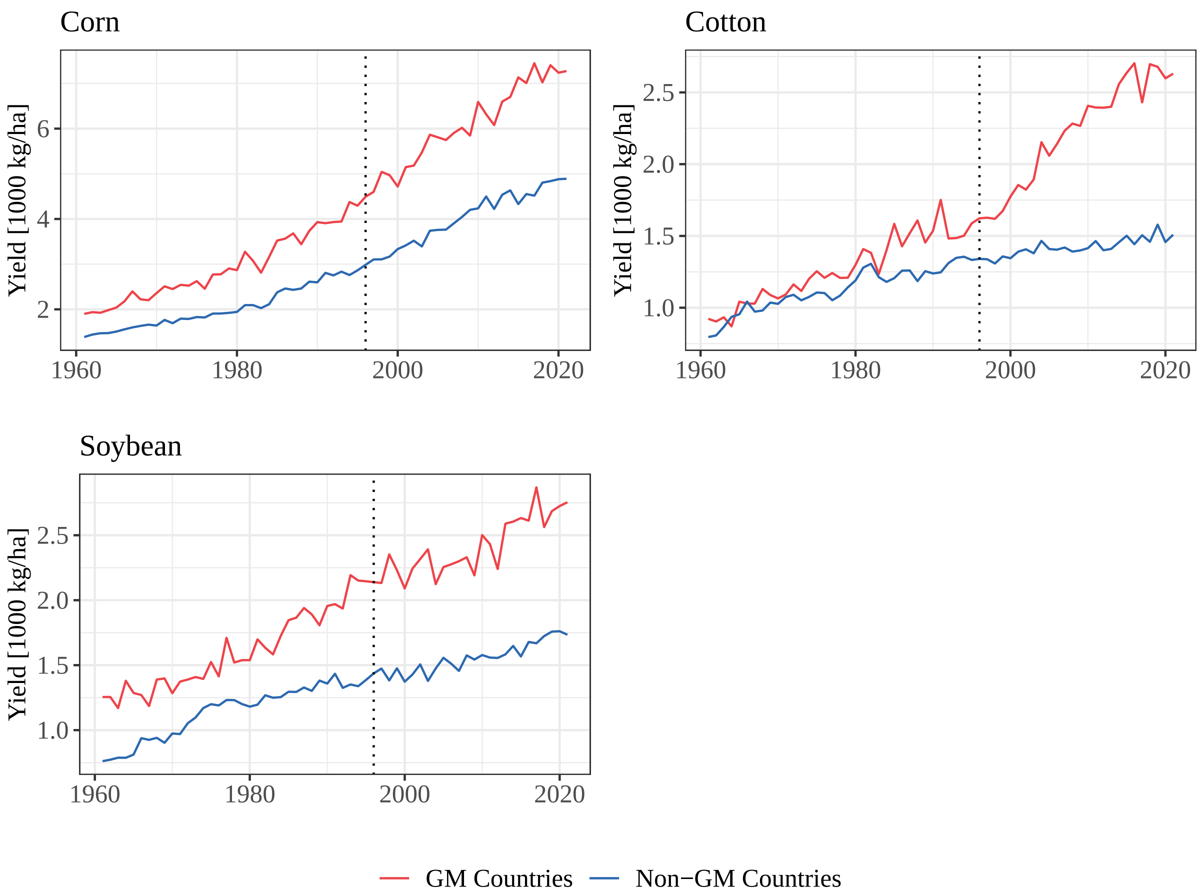

Figure 3: GM crop adoption and crop yields. The red lines are mean crop yields for countries with at least 10 % adoption of GM corn, cotton, and soybeans in 2018, respectively. The blue lines are the mean crop yields for the other countries. The dotted line is the year of GM commercialization (1996), after which adopting countries started to increase the share of land under GM varieties. The GM adoption data are from the status reports of the ISAAA ((*34*) to (*35*)). The yield data are from the Food and Agriculture Organization of the United Nations (FAO) (*47*).

forest gain, depending on the magnitude of deforestation in adopting and non-adopting regions. Further, the effect depends on the response of prices to aggregate supply. For example, the land-sparing effect may be stronger in relatively closed economies with highly responsive prices, while exporting countries facing world prices may not experience the same land-sparing effect through the price mechanism. Although it is conceptually clear that increased crop production in one region can reduce agricultural expansion elsewhere, as explained above, it is difficult to empirically quantify where cropland would be reduced and by how much. Computable general equilibrium (CGE) models are often used to quantify these spatial relationships (e.g. (*54*)). For example, (*55*) found that the Green Revolution, characterized by the adoption of high-yielding crop varieties in low-income countries since the late 1960s, potentially prevented the conversion of 18 to 27 million hectares into farmland, thanks to localized production increases and subsequent price effects. However, caution is warranted when using CGE models because they rely on numerous parametrized relationships, which may introduce biases in the analysis, and it often remains unclear which land cover the expanding agriculture displaces.

Pesticide Use

The two main types of GM crops – Bt and HT – are each related to pesticide use but in different ways. The Bt trait provides resistance to lepidopteran insect pests, thus reducing the need for chemical insecticide sprays against these particular pests. Numerous studies have, indeed, found evidence that Bt crop adoption is associated with significant insecticide reductions, both in low-income and high-income countries (*41*, *56–58*). However, the influence of Bt crops on insecticide application may fluctuate over time depending on various factors, including farmers' management practices. First, Bt targets specific insect pests, often lepidopteran in cotton (e.g., bollworms) and lepidopteran or coleopteran in corn (e.g., corn borers, corn rootworm). Thus, as with other pesticides, non-target, secondary insect pests may proliferate, which could lead to a rebound effect in insecticide use (*59*). Second, pest populations can develop resistance to Bt, especially when farmers do not plant refuge areas with non-Bt crops (*58*, *60–62*) or repeatedly plant the same variety of Bt crop. For example, field-evolved resistance has been observed in corn rootworm, one of the most serious corn pests in the US (*63*). As with other pesticides, resistance to Bt can then lead to increased pesticide use. Evaluation of long-term data suggests that Bt technologies can remain effective for many years and that pest resistance buildup can be managed with agronomic and breeding strategies (*64*) such as crop rotations and diversifying the type of Bt planting (*65*).

In contrast, HT crops are designed to be tolerant to certain broad-spectrum herbicides (historically and most prominently, glyphosate) and are intended to be used in conjunction with herbicides. Thus, empirical studies report either no significant reduction in overall pesticide use following HT adoption (*31*) or a substantial increase in the quantity of herbicides used (*43*). Furthermore, HT crops can cause a substitution effect, where the broad-spectrum herbicides they tolerate, such as glyphosate, replace other specific herbicides used in conventional agriculture that might be more or less toxic (*66*). This substitution has led to a substantial increase in glyphosate usage since the mid-1990s, particularly in countries that have widely adopted HT crops (*67*).

Another indirect consequence of GM crop adoption is that a reduction in the diversity of crop types and herbicide-active ingredients has contributed to herbicide resistance development in weeds (*67*). New GM crop varieties with multiple resistances against herbicides, such as the addition (stacking) of a dicamba-tolerance trait, have been commercialized to control these weeds. The resulting increased use of this potentially more toxic and volatile herbicide raises new concerns for human health (acute and chronic conditions related to dicamba), damages to non-dicamba-tolerant crops on neighboring fields (*11*), and harm to non-target vegetation in surrounding ecosystems. We discuss further implications of pesticide changes for pollution, human health, and biodiversity in more detail below.

Health Effects from Pesticide Use

Analogous to the implications for agricultural expansion and deforestation, understanding the impacts of GM crop adoption on human health and environmental pollution necessitates examining both direct and indirect effects. Direct adverse effects on human health from GM crop consumption are now broadly considered to be negligible (*6*). The indirect consequences, especially those related to changes in farmers' pesticide use, are proving significant and are receiving increasing attention.

Pesticide exposure occurs through dermal contact, ingestion, or inhalation. Farmers, farmworkers, and those involved in pesticide production are likely to experience the greatest health impacts from GM-driven changes in pesticide use (*68*). Populations residing near agricultural fields and the general public are exposed to pesticides primarily through diet or air and water pesticide contamination. Thus, regional pesticide regulation and residue monitoring are important indicators (*69*). Pesticide regulations and guidelines vary worldwide, with low-income countries often lacking the resources to implement or enforce legislation to avoid elevated occupational pesticide risks, nor to adequately limit pesticide residues from the food supply chain (*69*). Thus, the health impacts of GM-driven changes in pesticides are likely to be magnified in low-income countries for both occupational and non-occupational communities.

Following the adoption of Bt crops, reductions in insecticide use have generally led to positive environmental and human health outcomes for farmers, farm workers, and consumers (*57*, *70*). For example, Kouser and Qaim (*71*), utilizing detailed panel data from India, demonstrated that Bt cotton adoption has prevented millions of insecticide poisoning incidents annually among smallholder farmers due to reduced spraying. These health benefits, however, may wane over time if insecticide use on Bt crops increases due to the emergence of Bt-resistant pests or the proliferation of pests unaffected by Bt technology (see above).

Quantifying the health and pollution effects of HT crop adoption is complex due to changes in both the volumes and types of herbicides used (i.e., substitution of broad-spectrum herbicides for more specific ones, especially glyphosate). While Nelson and Bullock (*72*) argue that changes in herbicide use led to a decrease in health hazards on the basis of acute toxicity metrics, the International Agency for Research on Cancer (IARC) (*73*) classifies glyphosate as a probable carcinogen and suggests a net increase in cancer risk (*74*). Beyond the active ingredients of the herbicides, adjuvants (compounds that enhance the spread and effectiveness of herbicides) also contribute to the overall impact of pesticide application. For example, common adjuvants used with glyphosate, such as polyethoxylated tallow amine (POEA), have been shown to be substantially more toxic to humans (*75*) than glyphosate alone, and adversely affect aquatic and terrestrial species (*12*, *76*), a point that we discuss further below.

The risk quotient, a common metric for pesticide toxicity that combines pesticide quantities with health risk factors (e.g., measured as the inverse of the amount lethal to half of a rat population), offers insight into pesticides' health effects (*77*, *78*). A study by Lee et al. (*79*) applied this metric and found that GM crop adoption in the USA initially reduced pesticide toxicity. Over time, however, toxicity levels rose, partly due to the development of pesticide resistance. Overall, it is important to note that *ex-ante* toxicity studies might be subject to three main biases: (1) pesticide toxicity measurements can be imprecise (*80*, *81*), (2) evaluation may focus only on active ingredients ignoring the toxicity of adjuvants (*75*, *76*, *82*), and (3) the studies may measure hazard (i.e., potential of harm; toxicity) instead of risk (i.e., probability of harm; the interaction of toxicity with exposure), potentially under- or overestimating the actual damage to humans and non-target species (*83*, *84*).

An alternative approach to assessing the health impacts of GM crops involves directly measuring health outcomes associated with GM crop adoption through causal inference methods. These methods leverage natural variations, such as differences in GM crop suitability across regions or variations in the distribution of environmental impacts (e.g., upstream and downstream of GM crop adoption), to establish the causal effects of GM crops on health. These methods were used in Brazil, where widespread adoption of HT soybeans led to increased glyphosate use (*7*, *85*). Dias et al. (*7*) found that HT crop adoption and the resulting rise in glyphosate levels in water significantly increased infant mortality, pre-term birth rates, and the occurrence of low birth weights. Similarly, Skidmore et al. (*85*) linked the heightened pesticide use to elevated childhood cancer rates, likely through water contamination.

While significant progress has been made in assessing the environmental and health impacts of pesticide changes due to GM crop adoption, considerable uncertainties remain. These uncertainties relate to the effects of changes in the type, amount, and application timing of pesticides used on GM fields.

Further Management Practices

GM crop adoption has been associated with changes in other management practices beyond pesticide use, though the evidence is sparse, and the overall environmental consequences of these changes are still largely unknown. First, GM crops, especially those tolerant to glyphosate, may have facilitated reduced tillage intensity, achieved through conservation tillage or no-till practices, due to more effective weed control (*86–88*). For example, Perry et al. (*89*) observe that glyphosate-tolerant soybeans have promoted the use of these practices, increasing conservation tillage and no-till by approximately 10% and 20%, respectively. While the impact of reduced tillage practices on productivity is mixed (*90*), they have been shown to benefit soil structure, runoff and water quality, soil biota and aboveground wildlife, and air quality, with varying levels of magnitude (*91–93*), and have mixed impacts on carbon sequestration (*94*, *95*) (see below).

Second, GM crop adoption may also influence crop rotation practices. Specifically, GM crops, by providing effective weed and pest control, might reduce the traditional yield advantages gained from rotating crops (*96*). This substitution effect could potentially reduce crop rotations at the field level and lead to more crop uniformity across larger agricultural landscapes, thereby reducing both temporal and spatial crop diversity. Causal evidence for this relationship has yet to be established. Understanding this relationship is crucial, as diverse crop rotations support wild biodiversity (*97*), reduce pesticide applications in the agricultural landscape (*98*), and enhance the resilience of agricultural systems to adverse weather conditions (*99*).

Finally, new crop varieties can encourage increased use of further inputs such as fertilizer (*100*), which can have profoundly harmful downstream consequences for the environment and human health (*101*).

Below, we discuss the implications of these management changes for biodiversity and greenhouse gas emissions.

Biodiversity

GM crop adoption can affect biodiversity directly through the consumption of GM crops or indirectly through various land use changes, including agricultural expansion, pesticide use, and other management practices. A vast amount of literature has examined the direct effects of GM crops on non-target species. Most studies focus on the effects of Bt crop consumption on a diversity of organisms; these studies have identified adverse toxic effects on a range of non-target species, including butterflies, springtails, and lacewings (*4*, *102–104*). While these studies highlight potential risks, they also underscore substantial gaps in our knowledge, particularly regarding aquatic, microbial, and soil-dwelling organisms (*105*, *106*). In addition, the concern has been raised that many studies are poorly replicated, conducted in non-field realistic conditions, and are often funded by industry stakeholders (*4*, *102*). Given these caveats, the available evidence suggests that, for the species tested, risks posed by direct and immediate contact with GM crops under field-realistic conditions appear small or non-existent (*5*).

The movement of transgenes into wild populations is another oft-cited risk of GM crop adoption (*107*). Gene flow from GM crops to wild or locally adapted crops could reduce biological diversity through genetic assimilation (*108*) or give rise to new lineages that persist (*109*). There is considerable evidence of gene flow from GM to wild species, for example, in the case of GM to wild canola varieties in Canada (*14*). At the same time, the fate of lineages resulting from transgenic gene flow is inherently difficult to predict (*110*) and, to date, the risk of negative environmental or economic impact appears to be low (*111*).

GM crop adoption has led to several changes in global pesticide usage (see above), and there is a clear scientific consensus that pesticides threaten biodiversity worldwide (*112–115*). In addition to the direct impacts of Bt and herbicides on wildlife living within GM crops, herbicide spray drift can lead to the loss of wild plant diversity in nearby landscapes, even at low concentrations (*116*). This loss of host plant diversity can impose negative downstream effects on key ecosystem players such as pollinators and other non-target organisms (*117*).

Finally, there is growing consensus that changes in agricultural management practices that reduce crop and landscape heterogeneity (i.e., agricultural simplification) also negatively affect biodiversity. For instance, Strobl (*97*) found that greater crop diversity is linked to higher bird diversity in agricultural landscapes. Furthermore, a comprehensive meta-analysis by Sirami et al. (*118*) provided evidence that agricultural landscape simplification is associated with lower multi-trophic biodiversity. Agricultural expansion, when it occurs at the expense of natural and semi-natural habitats, is the single largest cause of biodiversity loss through wildlife habitat loss and degradation (*119*, *120*). Both types of land use change – agricultural simplification and expansion into natural areas – have been linked to GM crop adoption (see above) – although the exact extent of GM crops' role in simplification and expansion remains uncertain. A recent study that evaluated the combined direct and indirect effects of GM crop adoption on bird diversity in the US found overall positive effects of GM crop adoption on bird diversity with heterogeneous effects across species groups and crops. While insectivorous birds benefitted from GM crop adoption, especially from GM cotton, herbivorous birds declined in response to GM crop

adoption, with GM soy having the strongest impact (*9*).
A major challenge in evaluating the risks associated with GM crops for biodiversity is the scarcity of standardized, long-term biodiversity data from agricultural landscapes. While reliable longitudinal bird survey data exist in some countries, such comprehensive data are lacking for other critical taxa, including insects, microbes, and plants. The absence of long-term biodiversity records for taxonomic groups heavily impacted by pesticides, such as insects and microbes, hinders a full understanding of GM crop management's effects on biodiversity (*121–124*). These groups, which also play crucial functional and trophic roles (e.g., as mutualists, prey, predators, and pathogens) in the same agro-environments, require more extensive research to fully grasp the broader impacts of GM crop adoption on biodiversity, particularly taxa with limited existing survey records.

Greenhouse Gas Emissions and Climate Change

GM crop adoption can affect greenhouse gas emissions through agricultural expansion and deforestation and changes in management practices on existing agricultural land, including tillage practices, fertilizer applications, the use of agricultural machinery, and shifts between crop and livestock production (*48*, *125*). Collectively, these changes could significantly impact greenhouse gas emissions (*15*). For instance, Kovak et al. (*48*) estimated that GM crop adoption in Europe could reduce agricultural greenhouse gas emissions by 7.5% due to higher yields and thus reduced agricultural expansion at the global level. In terms of tillage, adopting GM crops with the HT trait has facilitated no-till practices, reducing tractor and fuel use and possibly increasing soil carbon sequestration. However, the benefits of no-till agriculture for reducing greenhouse gas emissions are controversial and may require integration with other practices, including cover cropping and crop rotations (*90*, *95*). Further changes in greenhouse gas emissions can result from fertilizer adjustments (see above), but the impact of GM crop adoption on emissions from fertilizer use is largely unknown.
The prevailing view in the current literature is that GM crop adoption could be greenhouse gas-reducing (*48*, *125*), but substantial uncertainties over the magnitudes of greenhouse gas emissions still persist. So far, most GM crop applications are found in conventionally-managed systems with relatively high greenhouse gas emissions per unit of land.

Outlook

GM crop adoption has been rapid and complete throughout several of the major crop-producing countries in the world. However, the adoption is mostly confined to two GM traits (HT and Bt) and a small number of commercial crops. While some countries embraced these GM technologies, others, including members of the European Union and countries in Africa and Asia, still ban their production, mainly because of perceived environmental and health concerns.
Much progress has been made in recent years to quantify the impact of GM crop adoption on agricultural inputs and outcomes. Examples include the recent studies on pesticides (*79*) and yields (*46*). These studies are fundamental for understanding the pathways through which GM crop adoption could affect environmental and health outcomes. However, linking those individual management changes to the relevant outcomes is complicated by the number of pathways that could affect the outcomes. Examples are the indirect impacts of GM crops on biodiversity through changes in land use

and cover, pesticide toxicity, or species interactions. Focusing on individual impacts, such as pesticide toxicity, may lead to an incomplete picture of the overall effects. A growing literature, therefore, focuses on the combined indirect and direct effects of GM crop adoption on environmental and health outcomes using causal inference techniques and "natural" experiments. These studies include biodiversity (*9*), health (*7*), and forest cover (*8*).

In spite of the substantial progress, large knowledge gaps remain. First, large uncertainties persist about the long-term impact of GM crops on the expansion of monocultures and the spread of resistant weeds and pests. These changes may diminish or even reverse the short-term benefits of pesticide reductions from GM crop adoption (*79*). Second, the long-term impact of GM crop adoption on species groups other than birds, including bees, butterflies, and other insects, is largely unassessed. These groups may be directly affected by GM crops and pesticide use changes, and their abundance and diversity may, in turn, directly affect agricultural production (*126*). The lack of systematic long-term surveys of these species groups hampers the progress in this field. Third, the quantification of GM crop adoption on deforestation on a global scale has not been quantified. Although local deforestation effects have been demonstrated, e.g., in Brazil where deforestation was enhanced (*8*), the often assumed reduction of deforestation at a global scale in response to GM crop adoption has not been tested empirically.

It is important to note that the environmental consequences of GM crop adoption evaluated here have largely been assessed in similar farming systems, namely, simplified conventional monoculture systems, setting a low bar for environmental comparisons. Such simplified systems are known to substantially reduce both biodiversity and ecosystem services relative to more diversified forms of agriculture (*127–129*). Thus, any positive environmental effects of GM crops, such as improvements to bird biodiversity (*9*), must be interpreted cautiously. While GM crops that maintain or increase yields while reducing environmental harm may be developed, it is critical to go beyond harm reduction towards regenerating environmental benefits to achieve agricultural sustainability.

While this review finds mixed effects of current GM crops on the environment, it is important to remember that current GM crop production is dominated by a few GM-crop-trait combinations that were selected in a process driven by industry self-interests, public acceptance (or lack thereof), and costly regulation. It is plausible that GM crops with other traits explicitly developed to reduce the environmental impacts of agriculture combined with stringent resistance management efforts would have unambiguous positive environmental consequences. New gene-editing tools can reduce the cost and increase the speed and precision of developing desirable traits. However, this will require a conducive policy and regulatory environment that fosters diversity, transparency, sustainability, and a less concentrated industry (*32*, *130*). Finally, GM and gene-edited crops and traits should not be seen as a substitute for good agronomic practices but should be integrated smartly into sustainable production systems.

References

1. L. T. Hickey *et al.*, Breeding crops to feed 10 billion. *Nature biotechnology* **37**, 744–754 (2019).

2. S. Zaidi *et al.*, New plant breeding technologies for food security. *Science* **363**, 1390–1391 (2019).

3. Hazel, Jonny and Jones, Jonathan, *Enabling Genetic Technologies for Food Security: Policy Briefing* (The Royal Society, London, 2023), ISBN: 978-1-78252-682-7.

4. M. Marvier, C. McCreedy, J. Regetz, P. Kareiva, A meta-analysis of effects of Bt cotton and maize on nontarget invertebrates. *Science* **316**, 1475–1477 (2007).
5. M. Meissle, S. E. Naranjo, J. Romeis, Does the growing of Bt maize change abundance or ecological function of non-target animals compared to the growing of non-GM maize? A systematic review. *Environmental Evidence* **11**, 21 (2022).
6. National Academies of Sciences, Engineering, and Medicine, *Genetically Engineered Crops: Experiences and Prospects* (The National Academies Press, Washington, DC, 2016), ISBN: 978-0-309-43738-7.
7. M. Dias, R. Rocha, R. R. Soares, Down the River: Glyphosate Use in Agriculture and Birth Outcomes of Surrounding Populations. *Review of Economic Studies* **90**, 2943–2981 (2023).
8. I. Carreira, F. Costa, J. P. Pessoa, The deforestation effects of trade and agricultural productivity in Brazil. *Journal of Development Economics* **167**, 103217 (2024).
9. D. Engist, M. Guzman, A. Larsen, T. Church, F. Noack, The impact of genetically modified crops on bird diversity. *Nature Sustainability*, Accepted (2024).
10. W. D. Hutchison *et al.*, Areawide suppression of European corn borer with Bt maize reaps savings to non-Bt maize growers. *Science* **330**, 222–225 (2010).
11. A. Missirian, Yes, in your backyard: Forced technological adoption and spatial externalities. *TSE Working Papers* (2024).
12. G. Schütte *et al.*, Herbicide resistance and biodiversity: agronomic and environmental aspects of genetically modified herbicide-resistant plants. *Environmental Sciences Europe* **29**, 1–12 (2017).
13. A. R. Kniss, Genetically engineered herbicide-resistant crops and herbicide-resistant weed evolution in the United States. *Weed Science* **66**, 260–273 (2018).
14. G. Barrows, S. Sexton, D. Zilberman, Agricultural biotechnology: the promise and prospects of genetically modified crops. *Journal of Economic Perspectives* **28**, 99–120 (2014).
15. G. Barrows, S. Sexton, D. Zilberman, The impact of agricultural biotechnology on supply and land-use. *Environment and Development Economics* **19**, 676–703 (2014).
16. J. Hargrave, K. Kis-Katos, Economic causes of deforestation in the Brazilian Amazon: a panel data analysis for the 2000s. *Environmental and Resource Economics* **54**, 471–494 (2013).
17. J. Fernandez-Cornejo *et al.*, "Pesticide Use in U.S. Agriculture: 21 Selected Crops, 1960-2008", tech. rep. EIB-124 (U.S. Department of Agriculture, Economic Research Service, 2014).
18. J. Assunção, C. Gandour, R. Rocha, Deforestation slowdown in the Brazilian Amazon: prices or policies? *Environment and Development Economics* **20**, 697–722 (2015).
19. R. Miao, M. Khanna, H. Huang, Responsiveness of crop yield and acreage to prices and climate. *American Journal of Agricultural Economics* **98**, 191–211 (2016).
20. S. Savary *et al.*, The global burden of pathogens and pests on major food crops. *Nature Ecology and Evolution* **3**, 430–439 (2019).
21. J. Wesseler, R. D. Smart, J. Thomson, D. Zilberman, Foregone benefits of important food crop improvements in Sub-Saharan Africa. *PLoS One* **12**, e0181353 (2017).

22. Qaim, Matin, Role of new plant breeding technologies for food security and sustainable agricultural development. *Applied Economic Perspectives and Policy* **42**, 129–150 (2020).

23. AgbioInvestor, "Time and cost to develop a new GM trait", tech. rep. (AgbioInvestor. Pathhead (Midlothian), 2022).

24. B. Schiek, G. Hareau, A. Baguma Yona andMedakker, D. Douches, D. Shotkoski, Demystification of GM crop costs: Releasing late blight resistant potato varieties as public goods in developing countries. *International Journal of Biotechnology* **14**, 112–131 (2016).

25. R. Herring, R. Paarlberg, The political economy of biotechnology. *Annual Review of Resource Economics* **8**, 397–416 (2016).

26. M. F. Brennan, C. E. Pray, A. Courtmanche, "Impact of industry concentration on innovation in the US plant biotech industry", tech. rep.

27. P. H. Howard, Visualizing consolidation in the global seed industry: 1996–2008. *Sustainability* **1**, 1266–1287 (2009).

28. M. Qaim, A. De Janvry, Genetically modified crops, corporate pricing strategies, and farmers' adoption: the case of Bt cotton in Argentina. *American Journal of Agricultural Economics* **85**, 814–828 (2003).

29. USDA Agricultural Marketing Service, *More and Better Choices for Farmers: Promoting Fair Competition and Innovation in Seeds and Other Agricultural Inputs* (USDA, 2023).

30. R. Paarlberg *et al.*, The uptake of new crop science: Explaining success, and failure. *Food Policy* **122**, 102572 (2024).

31. J. Fernandez-Cornejo, S. J. Wechsler, M. Livingston, L. Mitchell, "Genetically Engineered Crops in the United States", tech. rep. ERR-162 (U.S. Department of Agriculture, Economic Research Service, 2014).

32. J. Clapp, The problem with growing corporate concentration and power in the global food system. *Nature Food* **2**, 404–408 (2021).

33. U. Aldana, B. Barham, J. Foltz, P. Useche, Early adoption, experience, and farm performance of GM corn seeds. *Agricultural Economics* **43**, 11–18 (2012).

34. ISAAA, *Global status of commercialized biotech/GM crops: 2004* (International Service for the Acquisition of Agri-biotech Applications, 2004).

35. 'ISAAA', *Global status of commercialized biotech/GM crops in 2019* (International Service for the Acquisition of Agri-biotech Applications, 2019).

36. C. James, *Global status of commercialized biotech/GM crops, 2007* (ISAAA Ithaca, NY, 2007), vol. 37.

37. B. Dhar, Sui generis systems for plant variety protection. *Quaker United Nations Office, Geneva* (2002).

38. D. Leskien, M. Flitner, *Intellectual property rights and plant genetic resources: options for a sui generis system* (Bioversity International, 1997).

39. S. Boettiger, G. Graff, P. G. Pardey, E. Van Dusen, B. D. Wright, Intellectual property rights for plant biotechnology: International aspects. *Handbook of plant biotechnology* **1**, 1088–1113 (2004).

40. ISAAA, *Indian Universities Develop Bt Cotton Varieties with Reusable Seeds*, `https://www.isaaa.org/kc/cropbiotechupdate/article/default.asp?ID=15257`, Accessed: Jan 9, 2024, 2017.

41. A. U. Ahmed, J. Hoddinott, N. Abedin, N. Hossain, The impacts of GM foods: results from a randomized controlled trial of Bt eggplant in Bangladesh. *American Journal of Agricultural Economics* **103**, 1186–1206 (2021).

42. J. Kathage, M. Qaim, Economic impacts and impact dynamics of Bt (Bacillus thuringiensis) cotton in India. *Proceedings of the National Academy of Sciences* **109**, 11652–11656 (2012).

43. W. Klümper, M. Qaim, A meta-analysis of the impacts of genetically modified crops. *PloS one* **9**, e111629 (2014).

44. K. Muralidharan, P. Niehaus, Experimentation at scale. *Journal of Economic Perspectives* **31**, 103–124 (2017).

45. C. A. Davis, A. M. Mobarak, The challenges of scaling effective interventions: A path forward for research and policy. *World Development* **127**, 104817 (2020).

46. C. W. Hansen, A. M. Wingender, National and Global Impacts of Genetically Modified Crops. *American Economic Review: Insights* **5**, 224–240 (2023).

47. *FAOSTAT*, `https://www.fao.org/faostat/en/#data`.

48. E. Kovak, D. Blaustein-Rejto, M. Qaim, Genetically modified crops support climate change mitigation. *Trends in Plant Science* **27**, 627–629 (2022).

49. T. Harding, J. Herzberg, K. Kuralbayeva, Commodity prices and robust environmental regulation: Evidence from deforestation in Brazil. *Journal of Environmental Economics and Management* **108**, 102452 (2021).

50. C. Balboni, A. Berman, R. Burgess, B. A. Olken, The economics of tropical deforestation. *Annual Review of Economics* **15**, 723–754 (2023).

51. N. Berman, M. Couttenier, A. Leblois, R. Soubeyran, Crop prices and deforestation in the tropics. *Journal of Environmental Economics and Management* **119**, 102819 (2023).

52. R. Abman, C. Carney, Agricultural productivity and deforestation: Evidence from input subsidies and ethnic favoritism in Malawi. *Journal of Environmental Economics and Management* **103**, 102342 (2020).

53. B. Dalheimer, C. Kubitza, B. Brümmer, Technical efficiency and farmland expansion: Evidence from oil palm smallholders in Indonesia. *American Journal of Agricultural Economics* **104**, 1364–1387 (2022).

54. T. W. Hertel, N. Ramankutty, U. L. C. Baldos, Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO2 emissions. *Proceedings of the National Academy of Sciences* **111**, 13799–13804 (2014).

55. J. R. Stevenson, N. Villoria, D. Byerlee, T. Kelley, M. Maredia, Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production. *Proceedings of the National Academy of Sciences* **110**, 8363–8368 (2013).

56. J. Huang *et al.*, A decade of Bt cotton in Chinese fields: assessing the direct effects and indirect externalities of Bt cotton adoption in China. *Science China Life Sciences* **53**, 981–991 (2010).

57. P. C. Veettil, V. V. Krishna, M. Qaim, Ecosystem impacts of pesticide reductions through Bt cotton adoption. *Australian Journal of Agricultural and Resource Economics* **61**, 115–134 (2017).

58. A. J. Gassmann, D. D. Reisig, Management of insect pests with Bt crops in the United States. *Annual Review of Entomology* **68**, 31–49 (2023).

59. V. V. Krishna, M. Qaim, Bt cotton and sustainability of pesticide reductions in India. *Agricultural Systems* **107**, 47–55 (2012).

60. K. R. Kranthi, G. D. Stone, Long-term impacts of Bt cotton in India. *Nature Plants* **6**, 188–196 (2020).

61. Y. Carriere *et al.*, Crop rotation mitigates impacts of corn rootworm resistance to transgenic Bt corn. *Proceedings of the National Academy of Sciences of the United States* **115**, 18385–18392 (31 2020).

62. P. Bagla, Hardy cotton-munching pests are latest blow to GM crops. *Science* **327**, 1439 (5972 2010).

63. A. J. Gassmann, J. L. Petzold-Maxwell, R. S. Keweshan, M. W. Dunbar, Field-evolved resistance to Bt maize by western corn rootworm. *PloS one* **6**, e22629 (2011).

64. B. E. Tabashnik, J. A. Fabrick, Y. Carrière, Global patterns of insect resistance to transgenic Bt crops: The first 25 years. *Journal of Economic Entomology* **116**, 297–309 (2023).

65. Y. Carrière *et al.*, Crop rotation mitigates impacts of corn rootworm resistance to transgenic Bt corn. *Proceedings of the National Academy of Sciences* **117**, 18385–18392 (2020).

66. M. Qaim, G. Traxler, Roundup Ready soybeans in Argentina: farm level and aggregate welfare effects. *Agricultural Economics* **32**, 73–86 (2005).

67. C. M. Benbrook, Trends in glyphosate herbicide use in the United States and globally. *Environmental Sciences Europe* **28**, 1–15 (2016).

68. B. G. S. Pinto, T. K. M. Soares, M. A. Linhares, N. C. Ghisi, Occupational exposure to pesticides: Genetic danger to farmworkers and manufacturing workers–A meta-analytical review. *Science of the Total Environment* **748**, 141382 (2020).

69. C. E. Handford, C. T. Elliott, K. Campbell, A review of the global pesticide legislation and the scale of challenge in reaching the global harmonization of food safety standards. *Integrated environmental assessment and management* **11**, 525–536 (2015).

70. S. J. Smyth, The human health benefits from GM crops. *Plant Biotechnology Journal* **18**, 887 (2020).

71. S. Kouser, M. Qaim, Impact of Bt cotton on pesticide poisoning in smallholder agriculture: A panel data analysis. *Ecological Economics* **70**, 2105–2113 (2011).

72. G. C. Nelson, D. S. Bullock, Simulating a relative environmental effect of glyphosate-resistant soybeans. *Ecological Economics* **45**, 189–202, ISSN: 09218009 (2003).

73. IARC, *Some organophosphate insecticides and herbicides: IARC monographs on the evaluation of carcinogenic risks to humans*, vol. 112, pp. 1–452, ISBN: 978-92-832-0178-6, (`https://www.iarc.fr/featured-news/media-centre-iarc-news-glyphosate/`).

74. M. Desquilbet, D. S. Bullock, F. M. D'Arcangelo, A discussion of the market and policy failures associated with the adoption of herbicide-tolerant crops. *International Journal of Agricultural Sustainability* **17**, 326–337, ISSN: 1747762X (2019).

75. N. Defarge *et al.*, Co-formulants in glyphosate-based herbicides disrupt aromatase activity in human cells below toxic levels. *International Journal of Environmental Research and Public Health* **13** (2016).

76. I. M. Meftaul *et al.*, Controversies over human health and ecological impacts of glyphosate: Is it to be banned in modern agriculture? *Environmental Pollution* **263**, 114372 (2020).

77. E. D. Perry, G. Moschini, Neonicotinoids in US maize: insecticide substitution effects and environmental risk. *Journal of Environmental Economics and Management* **102**, 102320 (2020).

78. A. R. Kniss, Long-term trends in the intensity and relative toxicity of herbicide use. *Nature communications* **8**, 1–7 (2017).

79. S. Lee, G. Moschini, E. D. Perry, Genetically engineered varieties and applied pesticide toxicity in US maize and soybeans: Heterogeneous and evolving impacts. *Ecological Economics* **211**, 107873 (2023).

80. C. Portier *et al.*, Differences in the carcinogenic evaluation of glyphosate between the International agency for research on cancer (IARC) and the European food safety authority (EFSA). *Journal of Epidemiology and Community Health* **70**, 741–745 (8 2016).

81. C. J. Portier, A comprehensive analysis of the animal carcinogenicity data for glyphosate from chronic exposure rodent carcinogenicity studies. *Environmental Health: A Global Access Science Source* **19**, 1–18 (1 2020).

82. C. M. Benbrook, Why Regulators Lost Track and Control of Pesticide Risks: Lessons From the Case of Glyphosate-Based Herbicides and Genetically Engineered-Crop Technology. *Current Environmental Health Reports* **5**, 387–395 (2018).

83. T. R. Stafford, L. B. Best, Bird response to grit and pesticide granule characteristics: Implications for risk assessment and risk reduction. *Environmental Toxicology and Chemistry* **18**, 722–733 (1999).

84. D. R. J. Moore, D. L. Fischer, R. S. Teed, S. I. Rodney, Probabilistic risk-assessment model for birds exposed to granular pesticides. *Integrated Environmental Assessment and Management* **6**, 260–272 (2010).

85. M. E. Skidmore, K. M. Sims, H. K. Gibbs, Agricultural intensification and childhood cancer in Brazil. *Proceedings of the National Academy of Sciences* **120**, e2306003120 (2023).

86. S. Sankula, G. Marmon, E. Blumenthal, *Biotechnology-derived crops planted in 2004: impacts on US agriculture* (National Center for Food and Agricultural Policy Washington, DC, 2005).

87. J. Fernandez-Cornejo, C. Hallahan, R. F. Nehring, S. Wechsler, A. Grube, Conservation tillage, herbicide use, and genetically engineered crops in the United States: The case of soybeans. *AgBioForum* **15**, 231–241 (2013).

88. W. A. Givens *et al.*, Survey of tillage trends following the adoption of glyphosate-resistant crops. *Weed technology* **23**, 150–155 (2009).

89. E. Perry, G. Moschini, D. A. Hennessy, Testing for complementarity: Glyphosate tolerant soybeans and conservation tillage. *American Journal of Agricultural Economics* **98**, 765–784 (2016).

90. C. M. Pittelkow *et al.*, Productivity limits and potentials of the principles of conservation agriculture. *Nature* **517**, 365–368 (2015).

91. J. M. Holland, The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. *Agric. Ecosyst. Environ.* **103**, 1–25 (2004).

92. A. P. Behrer, D. Lobell, Higher levels of no-till agriculture associated with lower PM2. 5 in the Corn Belt. *Environmental Research Letters* **17**, 094012 (2022).

93. F. Cozim-Melges *et al.*, Farming practices to enhance biodiversity across biomes: a systematic review. *npj Biodiversity* **3**, 1 (2024).

94. J. M. Baker, T. E. Ochsner, R. T. Venterea, T. J. Griffis, Tillage and soil carbon sequestration—What do we really know? *Agric. Ecosyst. Environ.* **118**, 1–5 (2007).

95. R. S. Nicoloso, C. W. Rice, Intensification of no-till agricultural systems: An opportunity for carbon sequestration. *Soil Science Society of America Journal* **85**, 1395–1409 (2021).

96. J.-P. Chavas, G. Shi, J. Lauer, The effects of GM technology on maize yield. *Crop Science* **54**, 1331–1335 (2014).

97. E. Strobl, Preserving local biodiversity through crop diversification. *American Journal of Agricultural Economics* **104**, 1140–1174 (2022).

98. A. E. Larsen, F. Noack, Identifying the landscape drivers of agricultural insecticide use leveraging evidence from 100,000 fields. *Proceedings of the National Academy of Sciences* **114**, 5473–5478 (2017).

99. T. M. Bowles *et al.*, Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. *One Earth* **2**, 284–293 (2020).

100. K. Emerick, A. De Janvry, E. Sadoulet, M. H. Dar, Technological innovations, downside risk, and the modernization of agriculture. *American Economic Review* **106**, 1537–1561 (2016).

101. C. A. Taylor, G. Heal, Fertilizer and Algal Blooms. *Risks in Agricultural Supply Chains*, 83 (2023).

102. M. Cuhra, Review of GMO safety assessment studies: glyphosate residues in Roundup Ready crops is an ignored issue. *Environ. Sci. Eur.* **27**, 1–14 (2015).

103. D. A. Andow, C. Zwahlen, Assessing environmental risks of transgenic plants. *Ecol. Lett.* **9**, 196–214 (2006).

104. N. Defarge, M. Otto, A. Hilbeck, A roundup herbicide causes high mortality and impairs development of chrysoperla carnea (stephens) (neuroptera: chrysopidae). *SSRN Electronic Journal* **11** (2023).

105. H. J. Venter, T. Bøhn, Interactions between Bt crops and aquatic ecosystems: a review. *Environmental Toxicology and Chemistry* **35**, 2891–2902 (2016).

106. A. Pott, M. Otto, R. Schulz, Impact of genetically modified organisms on aquatic environments: Review of available data for the risk assessment. *Science of the Total Environment* **635**, 687–698 (2018).

107. N. C. Ellstrand, When Transgenes Wander, Should We Worry? *Plant Physiology* **125**, 1543–1545 (2001).

108. D. A. Levin, J. Francisco-Ortega, R. K. Jansen, Hybridization and the extinction of rare plant species. *Conservation biology* **10**, 10–16 (1996).

109. N. Ellstrand, P. Meirmans, J. Rong, K. Vrieling, D. Hooftman, Introgression of Crop Alleles into Wild or Weedy Populations. *Annual Review of Ecology, Evolution, and Systematics* **44**, 325–345 (2013).

110. B.-R. Lu, X. Yang, N. C. Ellstrand, Fitness correlates of crop transgene flow into weedy populations: a case study of weedy rice in China and other examples. *Evolutionary applications* **9**, 857–870 (2016).

111. N. Ellstrand, L. Rieseberg, When gene flow really matters: gene flow in applied evolutionary biology. *Evolutionary Applcations* **9**, 833–836 (2016).

112. M. A. Tsiafouli *et al.*, Intensive agriculture reduces soil biodiversity across Europe. *Global change biology* **21**, 973–985 (2015).

113. F. H. Tang, M. Lenzen, A. McBratney, F. Maggi, Risk of pesticide pollution at the global scale. *Nature Geoscience* **14**, 206–210 (2021).

114. J. Candel, G. Pe'er, R. Finger, Science calls for ambitious European pesticide policies. *Nature Food* **4**, 272–272 (2023).

115. Y. Li, R. Miao, M. Khanna, Neonicotinoids and decline in bird biodiversity in the United States. *Nature Sustainability* **3**, 1027–1035 (2020).

116. B. Strandberg *et al.*, Effects of glyphosate spray-drift on plant flowering. *Environ. Pollut.* **280**, 116953 (2021).

117. Y. L. Dupont, B. Strandberg, C. Damgaard, Effects of herbicide and nitrogen fertilizer on non-target plant reproduction and indirect effects on pollination in Tanacetum vulgare (Asteraceae). *Agric. Ecosyst. Environ.* **262**, 76–82 (2018).

118. C. Sirami *et al.*, Increasing crop heterogeneity enhances multitrophic diversity across agricultural regions. *Proceedings of the National Academy of Sciences* **116**, 16442–16447 (2019).

119. L. Kehoe *et al.*, Biodiversity at risk under future cropland expansion and intensification. *Nature ecology & evolution* **1**, 1129–1135 (2017).

120. D. Tilman *et al.*, Future threats to biodiversity and pathways to their prevention. *Nature* **546**, 73–81 (2017).

121. E. V. S. Motta, K. Raymann, N. A. Moran, Glyphosate perturbs the gut microbiota of honey bees. *PNAS* **115**, 10305–10310 (2018).

122. M.-P. Hébert *et al.*, Widespread agrochemicals differentially affect zooplankton biomass and community structure. *Ecological Applications* **31**, e02423 (2021).

123. A. Weidenmuller, A. Meltzer, S. Neupert, A. Schwarz, C. Kleineidam, Glyphosate impairs collective thermoregulation in bumblebees. *Science* **376**, 1122 (2016).

124. S. Klatyik *et al.*, Aquatic ecotoxicity of glyphosate, its formulations, and co-formulants: evidence from 2010 to 2023. *Environmental Sciences Europe* **36** (2024).

125. D. Da Mata, M. Dotta, T. Lobo, Technological Progress and Climate Change: Evidence from the Agricultural Sector. *SSRN* (2023).

126. M. Dainese *et al.*, A global synthesis reveals biodiversity-mediated benefits for crop production. *Science advances* **5**, eaax0121 (2019).

127. G. Tamburini *et al.*, Agricultural diversification promotes multiple ecosystem services without compromising yield. *Science advances* **6**, eaba1715 (2020).

128. D. Beillouin, T. Ben-Ari, E. Malézieux, V. Seufert, D. Makowski, Positive but variable effects of crop diversification on biodiversity and ecosystem services. *Global Change Biology* **27**, 4697–4710 (2021).

129. L. C. Ponisio *et al.*, Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society B: Biological Sciences* **282**, 20141396 (2015).

130. CAST, "Applications, Benefits, and Challenges of Genome Edited Crops", tech. rep. (Council for Agricultural Science and Technology (CAST), Ames, Iowa, 2024).

Acknowledgements

We are grateful for the constructive comments of the editor, Dr Bianca Lopez, and the two anonymous reviewers. Further, we thank Sylvia Heredia for her excellent help with the overview figure.
Funding: FN acknowledges support from the Canada Research Chairs Program (Canada Research Chair in Economic and Environmental Interactions). FN, RS, and ES-R acknowledge support from the SSHRC Insight Grant (# AWD-021156). RS and FN acknowledge funding from UBC's Faculty of Land and Food Systems Internal Research Grant and Grants for Catalyzing Research Clusters to UBC's Biodiversity Research Centre. MQ acknowledges support from Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) (# EXC-2070-390732324-PhenoRob). AL acknowledges support from the Agriculture and Food Research Initiative of the National Institute of Food and Agriculture, USDA (# 2022-67019-36397, #2023-68016-40683) and the US National Science Foundation (#2042526). LMG acknowledges funding from NSERC (Natural Sciences and Engineering Research Council of Canada) Discovery Grant.
Competing interests: All authors declare no competing interest.