CLIMATE CHANGE CONTRIBUTIONS FROM SEED AND CROP TECHNOLOGIES

Diego Macall, Peter Phillips, David Castle & Stuart Smyth

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Executive Summary

The objective of this report is to provide a summary of peer-reviewed literature for articles that provide evidence that innovations in plant breeding technologies and crop protection products, including biologicals, have contributed, or are contributing to climate change mitigation and adaption. While there are a range of technologies and products that contribute to climate change mitigation and adaption, much of the literature is directed to the development of genetically modified (GM) traits, their use in major commodity crops, the global adoption of GM crops, and responsive changes in production techniques. This is partly because the introduction of these contested traits have focused public research on their impacts and use. Jointly, these technologies and products are leading to significant contributions to climate change mitigation and adaptation. Overall, the literature steadily points to the accumulated impact of new technologies, especially GM crops, on the sustainability of crop production. The literature landscape analysis undertaken indicates that the literature is evolving and becoming more sophisticated, and qualitative improvements in research methodologies are emerging. As agriculture is called upon to make, and to precisely quantify, contributions to mitigation and adaption, there is likely to be pressure on the sector to improve the quantity and quality of published research, likely well beyond the relatively narrow focus on GM traits.

1. Introduction

The commercialization of genetically modified (GM) crops in the mid-1990s focused scholarly attention on the broad impacts of new technologies on the economic and ecological footprint of farming as it adapts and adopts to new possibilities. This literature provides significant evidence of benefits extending well beyond higher farm yields and reduced chemical usage. While there are an increasingly wide range of new technologies and products being directed to the global agri-food system, much of the evidence in the public domain is uniquely focused on this specific technological transformation. This report highlights the results from this literature, supplemented where available with evidence of the impact of other types of technology.

The International Service for the Acquisition of Agri-biotech Applications (ISAAA) provides annual reports on the global adoption of GM crops. According to the most recent report, covering 1996-2019, GM crops were grown on 190 million hectares in 29 countries, with 43 additional countries importing GM crops (ISAAA 2020). The top five GM adopting countries are the USA, Brazil, Argentina, Canada and India, accounting for 91% of global acreage. The leading GM crops are soybean (92 million ha), corn (61 million ha), cotton (26 million ha) and canola (10 million ha). Based on the global crop area for each crop, 79% of cotton, 74% of soybeans, 31% of corn and 27% of canola were GM varieties in 2019.

GM crop technologies are the most rapid instance of innovation diffusion and adoption in the history of agriculture (Khush 2012). Peer-reviewed research of most commercialized GM crops in most adopting countries establishes that GM crops contribute to yield increases and decreases of chemical inputs. The end result is that GM crops produce higher farm incomes, and the reductions in land management practices and chemical use have substantial environmental benefits.

As climates change and governments increasingly focus on mitigation and adaption strategies, innovation will continue to be the key to successfully achieving the objectives established through international treaties. As an innovative technology widely in use for 25 years, GM crops are capable of being an integral part of both climate mitigation and adaption. The adoption of GM crops establishes evidence of the contribution crop agriculture can make and has been making. The transition to new plant breeding technologies, such as genome editing are poised to extend and enhance the benefits achieved to date from GM crops.

1.1. Report Objective

This report provides a summary of peer-reviewed literature for articles that provide evidence that innovations in plant breeding technologies and crop protection products, including biologicals, have contributed, or are contributing to climate change mitigation and adaption.

2. Agricultural Innovation's Role in Climate Change Mitigation

2.1 Land Conservation

Higher yields and more resilient crops work to lower the pressure on land that otherwise might be left as forest, grasslands or wetlands. While seldom factored into climate strategies, this is probably one of the most significant contributions an innovation can make to climate change mitigation goals.

Tilman (1999), writing before the major biotechnological transformation, wrote that doubling of agricultural food production during the previous 35 years using innovations derived from traditional breeding systems was associated with a 6.87-fold increase in nitrogen fertilization, a 3.48-fold increase in phosphorus fertilization, a 1.68-fold increase in the amount of irrigated cropland, but only a 1.1-fold increase in land in cultivation. What he did not consider, however, is that in absence of more intensive production, more, often marginal, land would have needed to be brought into production, with the attendant loss of carbon sequestration in the soil and water systems. Extending this argument, the OECD has established 1960 as the point in time when increased production was decoupled from increased land utilization, confirming that from 1960-2020 land use increased 1.1-fold, while food production increased 3.9-fold (OECD 2021).

With the advent and widespread adoption of GM seeds, we have a new landscape to assess the impact of major technological change. Barrows et al. (2014) examine the impacts of GM crop production on the supply and use of land, finding that GM crops saved 13 million hectares of land from conversion to agriculture in 2010. A similar analysis a few years later shows that if there had been a global ban on GM crops, global cropland would have increased by 3.1 million hectares (Mahaffey et al. 2016). Of this newly needed cropland, 2.5 million hectares would be obtained from the conversion of pastureland, while the remaining 0.6 million hectares would be converted into cropland from global forests, generating a loss in the ecological services from trees.[1] Similarly, Taheripour et al. (2015) estimate if the US had banned rather than adopted GM crops, a significant amount of land would need to be converted from other crops, cropland pasture, pasture and forest to meet the global food demand.

Zhang et al. (2016) report that during 1996–2012 there was an increase of more than 370 million tons of food crops, with one-seventh of the increased yield attributed to GM crops in the US. To achieve an equal increase in yield as delivered by GM crops, they estimate the US would require an addition 300 million acres of conventional crops. These additional 300 million acres would necessarily be lands requiring more fertilizer or irrigation, and would be associated with deforestation and other land conversion causing serious ecological and environmental stress. A report from Graham Brookes and Peter Barfoot (2014) arrives as similar conclusions: for the period 1996–2013 they estimate that biotechnology was responsible for additional global production of 138 million tons of soybeans, 274 million tons of corn, 21.7 million tons of cotton lint and 8 million tons of canola. If those biotechnologies had not been available, to maintain equivalent production levels would have required an increment of 11% of the arable land in the US, or 32% of the cereal area in the EU. Current yield increase estimates from GM crops over the 1996-2020 period are 330 million tonnes of soybeans and 595 million tonnes of corn, with all yield increases worth US$261 billion (Brookes 2022).

These benefits contribute to the achievement of other environmental goals. For example, Phelan et al. (2011) tested the options of intensive farm management and less intensive 'land sharing' options and concluded that birds, for instance, were negatively affected by both practices, but were less harmed by intensive practices.

2.2 Carbon Sequestration

As GM crop adoption expanded during the late 1990s and early 2000s, farmers began to experience unrivaled efficiencies in weed control. Prior to herbicide tolerant crops, efficient in-crop weed control options were limited, resulting in farmers predominantly relying on the use of summerfallow for effective weed control. In dryland agricultural production, summerfallow practices resulted in significant soil erosion and loss, as well as reduced moisture conservation. GM

[1] The conversion of pastureland and forests into cropland would, in addition to being detrimental to biodiversity, release significant amounts of greenhouse gases into the atmosphere.

herbicide tolerant (HT) crops drove the transition from the use of tillage as the lead form of weed control, to continuous, zero tillage land management practices.

These effects have been reported in series of annual reports on the adoption of biotech crops completed by PG Economics.[2] This research was published in peer-reviewed articles by Graham Brookes and Peter Barfoot, the most recent of which estimates that 2.4 billion kg of CO_2 was sequestered by GM crop production in 2018 (Brookes and Barfoot 2020). The authors estimate this was the equivalent of removing over 1.6 million vehicles from the road for one year. The article additionally estimates that the reduction in tillage practices and adoption of zero tillage, has resulted in an extra 5.6 billion kg of carbon being sequestered in 2018 (equivalent to 20.6 billion kg of CO_2 not being released into the global atmosphere). These savings are equivalent to taking 13.6 million cars off the road for one year. Since 1996, an additional 302 billion kg of CO_2 has been sequestered as soil carbon.

Sutherland et al. (2021) surveyed Saskatchewan farmers, identifying that weed control provided by glyphosate was the leading technology driver that allowed farmers to virtually remove tillage from their operations, finding summerfallow decreased from 46% to 1% of hectares between 1991-94 and 2016-19. Carbon accounting results showed that in 1991-94, the average Saskatchewan hectare was a net carbon emitter, releasing 0.03 tonnes/year from tillage. By 2016-19, the average hectare became a net carbon sink, storing 0.12 t/yr from the combination of carbon no longer released from tillage and increased carbon storage from continuous crop production. Similarly, soil carbon storage from summerfallow reductions increased from 0.02 t/ha/yr in 1991-94 to 0.42 t/ha/yr in 2016-19. Summerfallow reductions increase SOC levels by reducing soil emissions from decomposition and increasing crop residues from continuous cropping.

Applying these values to total Saskatchewan crop production (15.2 million ha) indicates that reductions in tillage between 1991-94 and 2016-19 caused soils to go from being a net carbon emitter of 0.4 million tonnes per year (Mt/yr) to a net carbon sink of 1.9 Mt/yr. From reductions in summerfallow, Saskatchewan carbon storage increased from 0.3 Mt/yr to 6.4 Mt/yr. Canadian agriculture emits about 73 Mt CO_2 equivalents, or 20 Mt of carbon, each year. Carbon accounting results show that from 2016-19, Saskatchewan soils were annually storing 9-32% of total agricultural emissions from reductions in tillage and summerfallow. Additionally, Saskatchewan soils are

[2] For the list of their publications dating back to 2005, see: https://pgeconomics.co.uk/publications.

currently storing 3-11% of Canada's required emission reductions of 219 Mt CO_2 equivalents in the Paris Accord each year.

There is an abundance of literature on changes in land use, reductions in greenhouse gas (GHG) emissions and increases in carbon sequestration, but little of this literature frames the changes specifically as resulting from the adoption of GM crops. Awada et al. (2021), for example, built a model to account for different farming practices (i.e., conventional, minimum and zero tillage, summerfallow, crop rotations and residue retention) and input usage rates (i.e., fertilizer and fuel) to estimate how they affect GHG emissions in different soil climate zones and provinces in the Canadian Prairies region. The adoption of sustainable practices led to an 80% decline in GHG emissions in the crop sector between 1985 and 2016. While GM crops were not explicitly explored, they were noted as critical factor in opportunities to use advanced soil conservation methods and in reducing fertilizer and fuel usage.

Most scholars agree that increased carbon sequestration and the benefits of this are inextricably linked to the adoption of GM crops and the resulting changes in tillage and land management practices. Very few articles report specifically on the role of GM crops; consequently it is not possible to estimate what portion of the measured benefits are strictly due to GM crops. For example, Rattan Lal[3] at Ohio State University, a leading expert in carbon sequestration, has published extensively on increased carbon sequestration from changes in land use and increased crop intensification. Yet little of his research focuses on the impact of the adoption of GM crops despite wide recognition in the literature acknowledging that without GM crops most of the measured benefits would fail to exist.

Kern et al. (2012) undertook research quantifying the net balance of emitted and assimilated CO_2 due to the application of crop protection treatments on farms. The final CO_2 balance, considering GHG emissions due to on-farm crop protection treatment in comparison with CO_2 storage in additional biomass, CO_2 protected with respect to agrotechnical inputs and land inputs and CO_2 saved with respect to associated global land use changes, is positive and may reach multiples of up to nearly 2000. Their findings indicate that crop protection products in particular contribute to GHG emissions and mitigation in agriculture.

[3] See his website for a lengthy list of recent publications: https://senr.osu.edu/our-people/rattan-lal.

2.3 Changes in Chemical Use/Toxicity

One of the major purposes of GM seeds is to pair crop genetics with less toxic chemicals (in the case of weed management), to reduce chemicals (in the case of Bt traits) or to manage viral disease that might damage yields. Depending on the crop and the purpose, GM fields either use different chemicals, fewer chemicals or no chemicals. In a few developing countries some pairings have generated a greater use of chemicals, but mostly because weed or pest pressure was now manageable in a cost-effective way that did not previously exist.

One crop that has been extensively studied is canola. There is a general consensus that the amount of herbicide active ingredient per hectare for GM canola production in Canada has decreased, that herbicides are applied at lower rates, have lower environmental impact (EI) and that producer exposure has been reduced (Table 1). The Canola Council of Canada (2001) examined practices and impacts in 1999-2000, when approximately three-quarters of the canola acres were GMHT varieties. The study estimates that the lower herbicide-use on GMHT canola fields in Western Canada to be the equivalent of 6,000 fewer tonnes of herbicide application in 2000.

Table 1: Studies on canola herbicide use

Research study	Location	Study period	Herbicide volume	Change EI/ha
CCC 2001	Canada	1999/2000	- 40%	na
Brimner et al. 2005*	Canada	1995-2000	- 20%	- 37%
Kleter et al. 2007*	US	2004	- 30%	- 42%
Brookes & Barfoot 2010*	Canada & US	1996-2008	- 8%	- 16%
Leeson et al. 2006	Canada	1995-2003	- 12%	- 22%

Note: (*) indicates peer-reviewed publication.

Brimner et al. (2005) examined the changes in herbicide use due to GMHT canola adoption between 1995 and 2000, finding that herbicide use on conventional canola increased by 30% while herbicide use on GMHT canola decreased by 20%. They conclude that the EI for GMHT canola dropped 37%, but rose 56% for conventional canola. The authors noted that their study assumed GMHT canola was only sprayed with the corresponding herbicide and not tank-mixed with other herbicides, which could lead to under-estimating the actual application rate; conversely, they ignored any herbicides applied to conventional canola fields as a burn-off prior to seeding. Kleter et al. (2007) compared conventional and transgenic canola crops in the US over four years, finding that the application of herbicide active ingredient was 30% lower in GMHT canola than in conventional canola crops. The total EI per hectare was 42% lower, the ecological impact was 39% lower and the farmer impact was 54% lower. Brookes and Barfoot (2010) compared and aggregated environmental impact quotients (EIQ) values for GM and conventional crops in Canada and the US, concluding that between 1996 and 2008 the amount of active ingredient applied to canola decreased by 13.7 million kg or 18%, with a corresponding drop of 24% in EI. The study assumed that farmers applied herbicide at the recommended maximum level, which created the potential for over-estimation of application and underestimating the decline in usage and the net overall benefit. Leeson et al. (2006) examined trends in herbicide use in canola production, comparing weed surveys from the three Prairie provinces from 1995-97 against similar surveys from 2001-03, concluding that herbicide use dropped 12% and the EI fell 22% per hectare.

Significant changes in use and application of herbicides have occurred in canola weed management practices in Western Canada (Smyth et al. 2011). Comparing canola production in 1995 and 2006 the toxicity of herbicides applied to canola decreased by 53%, producer chemical exposure decreased by 55% and 1.3 million kg of chemical active ingredient that would have been applied with non-GM seeds was not applied. The cumulative environmental impact per hectare (EI/ha) of the top five herbicides applied in 1995 was 46,715, while the figure for the top five herbicides applied in 2006 was 29,458. If GMHT canola had not been developed and Canadian canola farmers continued to use previous production technologies, the amount of active ingredient applied to control weeds in 2007 would have been 38% above what was actually applied. Brookes and Barfoot (2020) update the canola situation in Canada, estimating a reduction in chemical active ingredient of 34.3 million kg, representing a 35% reduction in the environmental impact.

Other crops have had similar impacts. In their most recent assessment of the environmental impacts from GM crops, Brookes and Barfoot (2020) identify that the production of GM soybeans in Canada from 1997-2018 resulted in the reduced application of 4.56 million kg of chemical active ingredient. This represents a 23% reduction in the EI of chemicals applied for soybean production. Applying the same assessment to soybean production in Brazil over the 1997-2018 period identified an increase of 24 million kg of chemical active ingredient, however, the environmental impact of the chemicals applied decreased by 7.2%. Regarding global soybean production, the authors identify an increase of 5 million kg of chemical active ingredient, an increase of 0.1%, which represents a reduction in the environmental impact of 12.9%. An important caveat to the change in global chemical active ingredient is that Brookes and Barfoot do not account for changes in the production of soybeans during the period, as soybean production in the US alone has increased by 20 million acres.[4] Additional acres of soybean production will account for increased chemical application without necessarily disclosing lower rates of application. Global soybean production has significantly increased since 1995, rising from 25 million metric tonnes (MMT) to 240 MMT.[5] The increased production of soybeans in Latin America between 1990 and 2016 has been staggering, with Argentina increasing by 286%, Brazil by 248%, Paraguay by 281% and Uruguay by 3,474%.

To better assess the nature and impacts of changes in pesticide use, an evaluation of chemical use by US corn and soybean farmers from 1998 to 2011 was conducted (Perry et al. 2016a). On average, adopters of GM glyphosate tolerant (GT) soybeans used 28% (0.30 kg/ha) more herbicide than non-adopters, adopters of GT corn used 1.2% (0.03 kg/ha) less herbicide than non-adopters and adopters of GM insect resistant corn used 11.2% (0.013 kg/ha) less insecticide than non-adopters. When pesticides are weighted by the EIQ, however, it was identified that (relative to non-adopters) GM adopters used about the same amount of soybean herbicides, 9.8% less of corn herbicides and 10.4% less of corn insecticides.

As assessment of atrazine use for corn production in Wisconsin examined what impact atrazine use restrictions had on the range of weed management practices (Dong et al. 2017). A survey of farmers was done to gather data from both within areas where atrazine restrictions had been implemented and areas that had no restrictions. The results found that restricting the use of atrazine increased the adoption of herbicide tolerant (HT) corn varieties, which then contributed to an increase of conservation tillage practices. The combination of atrazine restrictions and increased HT corn production contributed to a reduction in herbicide modes of action that were being applied. They concluded that the reduction in the diversity of weed control options may contribute to an increase in the potential for herbicide resistance in weeds. The authors highlight that the regulatory efforts to restrict atrazine in groundwater might have the knock-on effect greater presence of herbicide resistant weeds, which may need to be controlled by tillage, which in turn works to increase soil erosion and a deterioration in water quality.

Cotton is also a major target, and the commercialization of Bt cotton resulted in substantial reductions in chemical application. Between 1996-2018, Brookes and Barfoot (2020) identify a

[4] See: https://www.agri-pulse.com/ext/resources/AgSummit/2017-SoyStats.pdf.
[5] See: https://aei.ag/2017/07/24/global-soybean-production/.

global reduction of 40 million kg of chemical active ingredient for HT cotton production, reducing the environmental impact of the chemical applied by 12.2%. Insect resistant cotton has resulted in a reduction of 331 million kg of active ingredient, a 34% reduction in environmental impact.

The 2002 commercialization of Bt cotton in India, with its millions of small landholders, provided an opportunity to assess GM crop adoption for developing world farmers. Qaim (2003) assessed Bt cotton adoption in India (based on 2001 field trials), noting that prior to commercialization, farmers were losing an estimated 50-60% of yields to insect pests. The analysis found that yields increased by an average of 58% and pesticide costs dropped by 50%. Subramanian and Qaim (2010) extended this research and report that after four years of production, Bt cotton yields were 37% higher and pesticide use dropped by 41%. Additional socio-economic benefits were also measured, with the most noticeable impact being increased use of paid female labor. Subramanian and Qaim estimated that Bt cotton-adopting households increased their incomes by 82% and households that were defined by the FAO as vulnerable (i.e., income of <US$2/day) increased their incomes by 134%.

Further research by Qaim (2014) shows that the application of cotton pesticides has fallen between 0.95-1.3kg/acre of active ingredient. This results in a cost savings of 879-1284 rupees (US$13-19) per acre. In India pesticides are applied by farmers walking through the field using a backpack sprayer, in most cases with little to no protective clothing. Millions of cases of acute pesticide poisonings are reported every year. The adoption of Bt cotton has reduced the number of cases of pesticide poisoning, estimated to range between 2.4 million and 9 million annually. This annually saves the Indian Ministry of Health an estimated US$14-51 million (Kouser and Qaim, 2011). Not only has the environment and farmer health benefited, but so too has yield and profitability of Bt cotton adopters. While adopters pay a higher price for seed, the cost is more than offset by the 24% increase in yield when compared to non-Bt cotton. Profits rose even more dramatically, by an estimated 1877 rupees (US$28) per acre or 50%. In 2012, it was estimated that 27 million acres were planted to Bt cotton, representing 95% of cotton production in India, generating a net gain for farmers of US$1 billion. Cotton production has increased in India to such an extent that it is now the global production leader.[6]

[6] See: https://www.ers.usda.gov/topics/crops/cotton-wool/cotton-sector-at-a-glance/#:~:text=The%20top%20two%20cotton%20producers,of%20cotton%2C%20surpassing%20China%20recently.

China has invested heavily in biotechnology and has been a strong adopter of Bt cotton. Based on a 1999 survey of cotton farmers in northern China, Pray and Huang (2003) provide the first insights into the impacts of Bt cotton. Their research measured economic, income distribution, environmental and health effects. While not easy to quantify due to farmer-to-farmer sales and seed saving from year-to-year, the authors estimate that early adoption ranged from 8-27%. The most substantial impacts from Bt cotton adoption is the environmental and health benefits resulting from reduced pesticide applications. The adoption of Bt cotton allowed farmers to spray less frequently, in some instances dropping from 30 applications per season to three, but more commonly from 12 to 3-4.

Huang et al. (2010) updated Chinese Bt cotton results following a decade of commercial production. They documented a drop in bollworm infestations, not only in Bt cotton fields, but in all cotton fields in parts of China. In some non-Bt cotton fields the amount of insecticide used dropped from in excess of 40 kg/ha to less than 10 kg/ha. Across the entire sample region insecticide applications dropped from 14 kg/ha to 4 kg/ha.

Similar reductions have been observed in the production of GMHT corn, with a reduction of 242 million kg of chemical active ingredient, a 12.1% reduction in the environmental impact (Brookes and Barfoot 2020). GM Bt corn has reduced chemical active ingredient application by 112 million kg, a 63% reduction in the environmental impact.

Other crops are only sparsely studied. The commercialization of Bt brinjal in Bangladesh has resulted in both a reduction in the amount of chemical applied in production, as well as a reduction in the EI of the chemicals applied. Ahmed et al. (2021) found Bt brinjal in Bangladesh has increased yield by 20%, decreased pesticide costs by 38%, and the toxicity of pesticides applied by 76%. Macall et al. (2020) found that 84% of farmers growing Bt corn in Honduras applied no pesticides, while yielding 50% higher.

In a wider assessment of literature that included journal articles, government reports as well as industry and organization reports, Klümper and Qaim (2014) report in their meta-analysis of 147 studies that chemical use declined by 37%, yields increased by 22% and farmer profits increased by 68%.

One study has been conducted that examines the potential economic and environmental impacts that would arise if restrictions on glyphosate use resulted in the world no longer planting

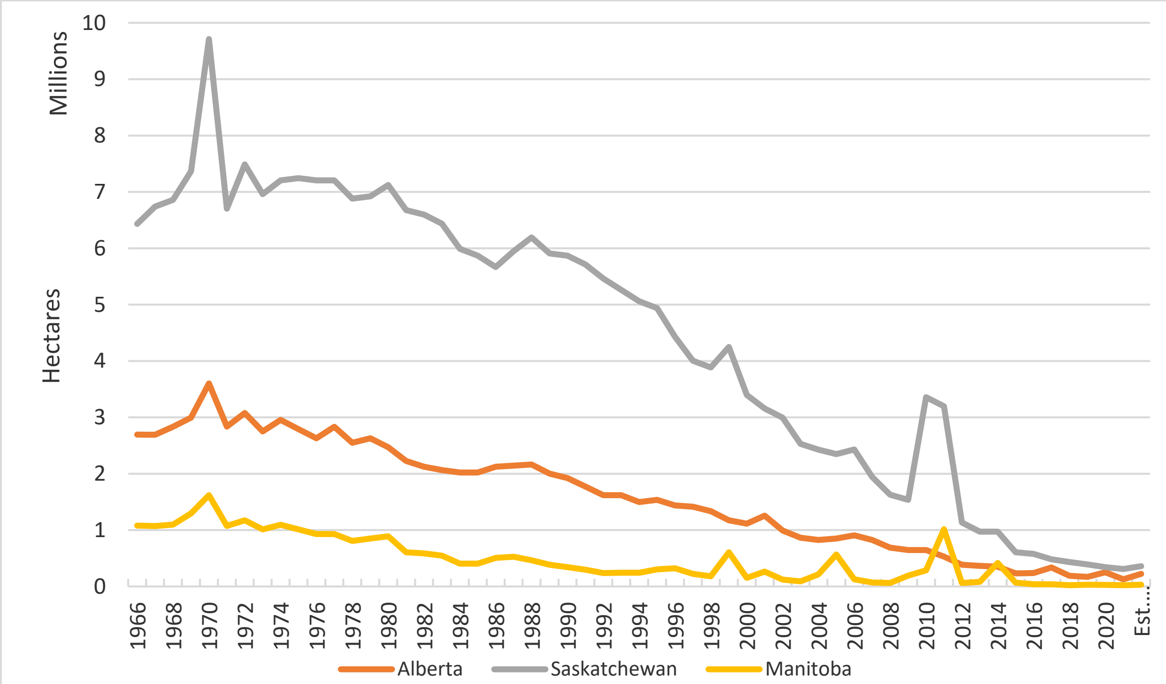
GMHT crops (Brookes et al. 2017). There would be an annual loss of global farm income gains of $6.76 billion and lower levels of global soybean, corn and canola production equal to 18.6 million tonnes, 3.1 million tonnes and 1.44 million tonnes respectively. There would be an annual environmental loss associated with a net increase in the use of herbicides of 8.2 million kg of herbicide active ingredient (+1.7%), and a larger net negative environmental impact, as measured by the EIQ indicator of a 12.4%. Also, there would be additional carbon emissions arising from increased fuel usage and decreased soil carbon sequestration, equal to the equivalent of adding 11.77 million cars to the roads.

A final, indirectly related, aspect of reduced chemical use is innovation in mechanical options. Walsh et al. (2012) assess one such innovation, the Harrington Seed Destructor, finding that viable weed seeds were reduced by greater than 95% when harvesting wheat, barley and lupins. The dispersion of weed seeds at harvest using normal combines and harvesters results in the need for herbicide applications the following spring. Using the seed destructor led to substantial reductions of weed seeds at harvest which created the opportunity for reduced herbicide applications in the subsequent crop years.

2.4 Changes in Greenhouse Gas Emissions

The improved ability to control weeds has resulted in farmers transitioning their land from having summerfallow as part of their crop rotations, to near full removal of summerfallow practices. Figure 1 illustrates just how significant this reduction has been across the Canadian prairie provinces of Alberta, Saskatchewan and Manitoba. In 1995, the first year GM canola was produced there was 6.8 million ha of summerfallow across the three provinces. By 2022, this dropped to 613,000 ha, a decrease of 91%.

Figure 1: Canadian prairie summerfallow area, 1966-2022



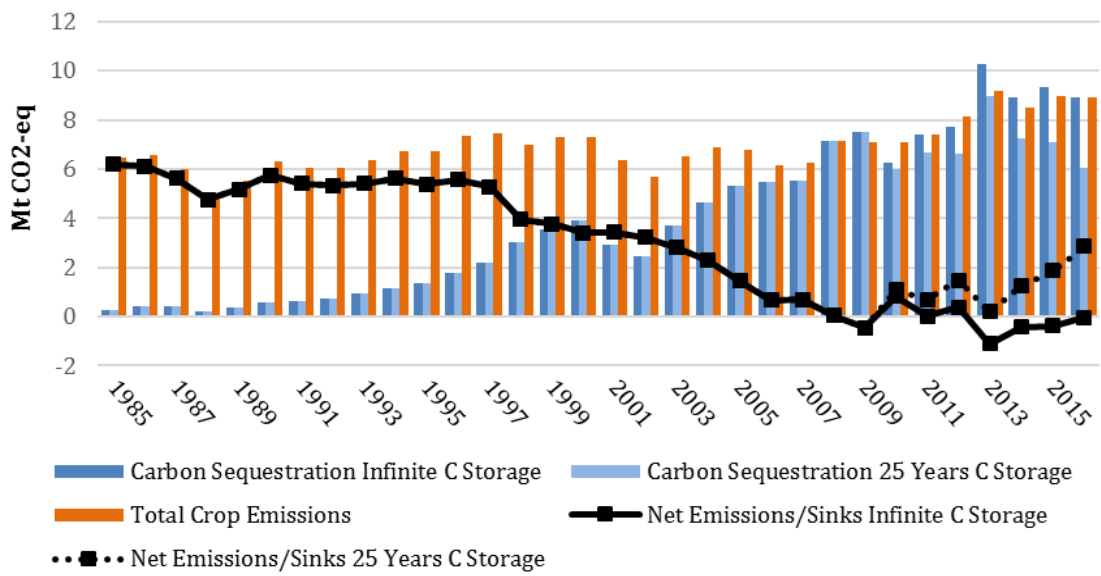
The reduction in summerfallow increases the area of crop production, which changes GHG emissions. Depending on the region of crop production, fewer field passes would be made by machinery when land is producing crops, compared with summerfallow. In other regions, there may be little difference. One estimate (Smyth and Awada 2018) of GHG emissions in Saskatchewan, indicates that since 2008, crop production has been a net carbon sink (Figure 2). Between 2013 and 2016, emissions remained relatively constant, with the continuous, zero tillage cropping resulting in increased carbon sequestration, hence the net GHG sink.

Economic studies which model the effects of conservation tillage adoption on soil properties have also shown positive impacts on carbon sequestration. A study by Grant et al. (2004) investigated how changes in management practices affect GHG emissions, finding that the average net reduction in emissions from converting to zero tillage was 0.61 Mg CO_2 equivalents per ha, per year in Canada.[7] As noted above, Awada et al. (2021) found the sustainable practices that combine better tillage and new genetics led to an 80% decline in GHG emissions in the Canadian prairie crop sector between 1985 and 2016. Since 2005, emissions dropped 53%, more than is required to meet

[7] One Mg represents one mega-gram, which is the equivalent of one metric tonne.

the 2030 Paris Accord target. In Alberta, crop production was a net GHG sink between 2013 and 2016 and between 2006 and 2016 in Saskatchewan.

Figure 2: Net GHG emissions/carbon sink in Saskatchewan's crop sector, 1985-2016



Shrestha et al. (2014) conducted a GHG inventory analysis of Canadian canola production between 1986–2006, finding that reductions in summerfallow sequestered 0.4 Mg CO_2 equivalents per ha, per year (ha/yr), while conservation tillage adoption sequestered 0.2 Mg CO_2 equivalents/ha/yr. MacWilliam et al. (2016) found that GHG emissions from one tonne of canola production decreased across all Canadian prairie soil zones from land use and land management changes between 1990 and 2010.

The delayed adoption of GM canola production in Australia was studied by Biden et al. (2018), finding that the delay cumulatively resulted in the application of an additional 6.5 million kg of chemical active ingredient. The application of these additional chemicals were done through an additional 7 million field passes, requiring 8.7 million liters of diesel. The environmental impact of the additional chemicals applied was 14% higher than would have been the case if GM canola had not been subjected to an adoption moratorium. Finally, an estimated 24 million additional kilograms of GHGs were released due to the non-adoption of GM canola.

An assessment of EU agricultural GHG emissions concluded that had the EU adopted GM crops in a timely fashion as North America, total emissions would be reduced by 7.5% of the EU's total agricultural GHG emission (Kovak et al. 2021). This amounts to 33 million tonnes of CO_2 annually.

2.5 Land Use Change

Herbicide tolerance allowed farmers to control a broad spectrum of weeds through in-crop applications without damaging crops. Farmers who grow HT canola are more likely to adopt conservation tillage practices (Hudson and Richards 2014; National Research Council 2010). Similar results have been seen in HT soybean production. In 1997, soon after the introduction of HT soybeans, twice the number of acres under no tillage were planted with HT soybean than those with conventional soybean in the US (Fernandez-Cornejo 2009). Results from a 2006 survey of 1,195 US farmers across six states (Iowa, Illinois, Indiana, Mississippi, North Carolina and Nebraska) found a complementary relationship between the adoption of conservation tillage and HT crops. Of farmers in the survey who had previously used conventional tillage, 56% adopted minimum or no tillage systems following the introduction of HT crops and 25% of farmers who had been practicing minimum tillage shifted to no tillage (Givens et al. 2009). Similar results from a 2009 survey of US farmers showed 80% of respondents believed there was less tillage in HT production than in conventional production (Harrington et al. 2009). The complementary relationship between these technologies has also been studied using economic and econometric modeling techniques. Numerous studies have concluded in favor of this relationship (e.g., Fernandez-Cornejo et al. 2002; Fernandez-Cornejo et al. 2013; Perry et al. 2016b).

To obtain adequate weed control in summerfallow, a minimum of 3-4 annual tillage operations were required in Western Canada (Molberg et al. 1967) and often up to eight passes were made, depending on the region (Carlyle 1997). Leaving a field to fallow also results in continued microbial activity and decomposition of available residue in the soil but lacks any residue input, an important factor in increasing soil organic carbon (SOC) stocks, leading to a decrease in soil organic matter (SOM) (Boehm et al. 2004; Mikha et al. 2010). The combined effect of the frequent tillage and lack of crop residue leads to increased soil erosion and in many cases, an unintended decrease in soil moisture. Consequently, SOC stocks typically decrease during fallow years (Ogle et al. 2005). Therefore, decreasing summerfallow area contributes to increased SOC levels by reducing soil emissions and through the shift to continuous cropping, increasing crop residue levels.

Studies looking at the impacts of reducing summerfallow have been conducted using modeling techniques. For example, Grant et al. (2004) modeled the impact of changes in management practices on Canadian emissions between 1979-2029. They predicted that the net emission reduction from the elimination of summerfallow would be 0.56 Mg CO_2 per ha, per year. In a study of the long-term farm management effects on SOC, Sperow (2016) used 2006 IPCC estimates for SOC factors to study the effects of reducing summerfallow. His results showed that the effects of eliminating summerfallow were relatively modest, increasing SOC stocks by 0.16-0.24 Mg C per ha, per year and contributing about 3% of total potential sequestration from all activities studied. More recently, Rosenzweig and Schipanski (2019) used satellite data to study cropping patterns in Colorado, Kansas and Nebraska, finding a decrease in summerfallow use from 48% to 33% of dryland cropland. The authors assessed the impacts of this cropping intensification on carbon sequestration, concluding that sequestration increased by 38% due to the adoption of mid-intensity and continuous rotations in place of summerfallow.

Continuous cropping increases crop residue levels, which contributes to increased accumulation of SOC (Campbell et al. 2002). Crop residues include any roots, stems or other plant material left in the field after harvest. The amount of crop residue is affected by crop yield and biomass. Early in the 20th century, crop residues were considered unfavorable and farmers correspondingly took steps to remove residues from their fields. Often, residues were burned or used as livestock feed and bedding. However, by 1980 the value of carbon sequestration and the beneficial contribution made by crop residues to reducing net GHG emissions began to be recognized.

Although many past studies assumed that the rate of carbon input to the soil is similar crop types, more recent studies have shown that above- and below-ground crop biomass, varies significantly between crop types. Carbon-to-nitrogen ratios impact changes in SOM and SOC levels as well. For example, soybeans have a relatively low carbon-to-nitrogen ratio and correspondingly, soybean crops typically result in lower carbon inputs to the soil (Hall and Russell 2019). Therefore, crop type is an important factor to consider when estimating changes in SOC. Gan et al. (2009) calculated carbon allocation coefficients for various crops which represent how much carbon is returned to the soil from each part of the plant relative to total carbon mass. They found, on average, that pulses had the greatest allocation coefficient for seed production and conversely, oilseeds had the greatest coefficient for straw. For all crops, the allocation coefficients for the roots were lower than for the grain or straw.

The reduction or elimination of disturbance to the soil layers in a minimum tillage or no tillage (NT) system also benefits farmers economically by reducing soil erosion, which has substantial effects on agronomic performance. Bakker et al. (2007) estimated that in mechanized agriculture, for every 0.1 m of soil loss, crop yields are reduced by 4% in the EU and North America. No tillage systems leave the majority of crop residues on the soil surface instead of incorporating them into the soil profile, which help to increase SOM content and decrease the negative impacts of erosion. Additionally, crop residues on the soil surface will reflect sunlight and conserve moisture by lowering the temperature of the soil and protecting it from high evaporation levels (Jarecki and Lal 2003; Sauer et al. 1996). All of these impacts have an effect on soil quality which affects agronomic performance and crop yield.

Carpenter (2011) examined the biodiversity impacts resulting from GM crop adoption, concluding that GM crops reduce the impact that agriculture has on biodiversity. The article reviews significant literature on the impacts of GM crops on crop diversity, non-target soil organisms, weeds, land use, non-target above-ground organisms and area-wide pest suppression. The review includes evidence from studies conducted in China, Denmark, Germany, Portugal, Switzerland and the USA.

2.6 Change in Soil Health

An important element of reducing net agricultural GHG emissions is improving levels of soil carbon sequestration. Carbon sequestration offsets positive emissions by transferring carbon from the atmosphere into secure soil storage pools through the process of photosynthesis. The CO_2 that is removed from the atmosphere by plants and transferred into the soil becomes soil organic carbon; thus, increases in SOC represent increased carbon sequestration. Each tonne of carbon in the soil represents about 3.67 tonnes of CO_2 sequestered in the past (McConkey et al. 2020). Capacity of the soil carbon storage pools are estimated to be four times the vegetation carbon pool and three times the atmospheric pool (Olson et al. 2017), with the capacity of each pool depending on soil characteristics, precipitation and climate (Lal 2004). The capacity of these storage pools are large, but previous studies have indicated they are finite (Powlson et al. 2011), with several previous studies estimating maximum storage pool capacities being reached 15-20 years after adoption of new management practices (Campbell et al. 2001; West and Post 2002). However, small changes in sequestration rates can cause substantial changes in carbon equilibrium timeframes (Nemo et al.

2017; Wutzler and Reichstein 2006). More recent studies suggest that through careful management, strategies may be developed to increase the sequestration potential of storage pools (Nath and Lal 2017). Paustian (2000) identifies three management practices that contribute to increased levels of SOC: 1) minimize soil disturbance and erosion; 2) maximize crop residue levels; and 3) maximize efficiency of water and fertilizer use. All three of these correlate to the adoption of GM crops, as decreasing the frequency of tillage operations and increasing cropping intensity by reducing summerfallow are strategies which help to achieve these goals.

Numerous soil science studies have examined the effects of conservation tillage adoption on carbon sequestration. While these studies do not necessarily identify the contributions of GM crops, GM crops have resulted in reduced tillage, therefore the results of increased soil conservation practices are applicable to the continuous cropping, zero tillage production of GM crops. In 2002, West and Post conducted a survey of the extensive soil science literature to quantify carbon sequestration rates, finding an average increase of 0.57±0.14 Mg carbon per ha, per year from conservation tillage adoption. McConkey et al. (2003) found SOC increases ranging from 0.067 – 0.512 Mg per ha, per year across Saskatchewan, with variations resulting from soil type and location. Liebig et al. (2005) studied emission mitigation strategies specifically in the Northwestern US and Canada, concluding that although the effects of crop management on SOC varied, no tillage systems in continuous, dryland cropping resulted in an average SOC increase of 0.27±0.19 Mg per ha, per year. More recently, Aziz et al. (2013) studied the impact of tillage practices on soil quality, which was defined based on an index made up of a range of biological, chemical and physical soil properties. Results of their study found that no till methods resulted in 30% higher soil carbon than conventional tillage. Similarly, Nath and Lal (2017) studied differences in soil aggregation and SOC resulting from changes in tillage practices. Results of their study showed that corn managed under a no tillage system sequestered 35-46% more carbon than conventionally tilled corn.

The positive effects of converting to NT systems may vary based on the time period and soil depths used for analysis. A meta-analysis by Angers and Eriksen-Hamel (2008) suggests that in the short-term, NT systems may not have a net positive contribution to SOC stocks due to accumulation of carbon at the soil surface. However, their results show that the benefits of a NT system likely increase with time (>10-15 years). Similar results from Blanco-Canqui and Lal (2008) indicate that gains to SOC as a result of decreased tillage are restricted to the surface soil layers. VandenBygaart et al. (2011) reported SOC increases in both the 0-15 and 15-30 cm depths in Western Canadian soils from the adoption of NT, yet improvements were higher in the 0-15 cm depth. Though conservation tillage systems might re-distribute residual carbon throughout the soil profile better than NT in the short-term, the net carbon gain resulting from a NT system in the long-term offsets this redistribution of carbon to deeper soil levels (Yanni et al. 2018).

A literature review and meta-analysis by Lee et al. (2014), indicated profitability increased for farmers using GM crops and conservation tillage and GM crop adoption are linked. The combined adoption of both technologies reduced agricultural impacts on the environment and often improved soil and water quality. Soil quality improvements have been associated with reduced tillage, decreased erosion and increased carbon sequestration, whereas water quality improvements are associated with greater post-emergent herbicide use that limit soil exposure and subsequent runoff.

The lack of proper soil nutrients are commonly the main factor limiting yields, particularly the nitrogen and phosphorus. The development of plant growth-promoting bacteria (PGPB) have been found to increase plant growth and plant biomass, reduce plant leaf water loss, enhance root development and increase photosynthetic efficiency (Fiodor et al. 2021). These crop enhancements were identified in the production of soybeans, corn, rice, tomatoes, peppers, sunflowers, canola, cotton, peanuts, oats, sugar cane and chickpeas. The ability to mitigate plant stresses through improved nutrient uptake, would result in a reduced reliance of synthetic fertilizers to provide adequate crop nutrients, helping to mitigate climate changes. To date, application of these technological innovations are limited to laboratory experiments and small plot evaluations and have not been approved for commercialization. Large scale adoption assessment would be needed to better quantify the impacts.

3. Literature Landscape Analysis

There are 5 key research domains into which the literature can be classified: carbon sequestration, chemical use change, GHG change, land use change and soil health. These domains can be assessed through these factors: agronomy, data, genetics and input use, farm structure/size, machinery and policy (Table 2). All of these factors contribute to increased yield, which will be highlighted as part of the assessments within the factors of agronomy and genetics, which would include the development of traits such as increased drought, heat and salinity tolerance. To quantify the matrix, a citation score will be used as a measure of the quality of the estimates. Most published articles provide citation scores and the cumulative score of the 10 most cited articles within each box provides one measure of the depth of research across the matrix, as well as how widely recognized the publications are. Because citations tend to increase over time, the range of publication dates will also be included for context. Undertaking the literature review that populates this matrix would be stage one of the report.

Table 2: Citation impact assessment matrix (# articles/average cites per year)

Assessment Factors	Area	Change in chemical use/toxicity	Carbon sequestration	GHGs	Land use change	Soil health
Agronomy	1/6	15/36	3/9	5/6	2/4	9/6
Data	--	3/47	1/5	--	1/6	2/6
Genetics	--	13/12	1/3	3/13	2/10	--
Farm structure	--	--	--	--	--	--
Machinery	1/15	1/15	--	--	1/45	3/21
Policy	3/7	1/1	--	2/8	--	--

This analysis offers a number of insights into chemical use.

a. The carbon sequestration literature establishes that the genetics provided by herbicide tolerant crops allows for changes in agronomic practices, predominantly the removal of tillage as a form of weed control. Data is limited, but the series of publications by Brookes and Barfoot establish that sufficient data exists at the GM crop adopting country level to estimate the national and global carbon sequestration volumes.

b. There is no evidence to date that changes in farm structure play a significant role. This is not to say that farm structure does not play a role, just that there is no literature to date that quantifies this relationship.

c. Similarly, there have been significant changes in seeding equipment over the past 30-40 years that have contributed to the ability of farmers to be better able to direct seed into the stubble of the previous crop, but no literature is available that quantifies any relationship to increased carbon sequestration.

d. Studies show that the genetics of herbicide tolerant and insect resistant crop innovations has resulted in significant agronomic impacts.

e. In comparisons with the production of commodities prior to the commercialization of GM varieties or in the production of non-GM varieties, evidence is amassing that confirms that GM crops reduce chemical applications. A meta-analysis quantifies the benefits of GM crops regarding reduced chemical usage based on the assessment of 147 separate pieces of literature. In many developing countries where small landholders have adopted GM crops, these applications will predominantly be by hand, resulting in reductions of pesticide poisonings. In industrial adopting countries, the applications will be done by mechanized sprayers, with the reduction in chemical use contributing to reductions in GHG emissions.

f. Again, there is no literature correlating changes in farm machinery with changes in chemical usage.

The evidence for GHG emissions is most often integrated with carbon sequestration. The evidence concludes that GHG emissions are reduced and carbon sequestration is increased. The leading driver of reduced emissions is the reduction in tillage practices and in-crop chemical applications. Increased carbon sequestration results from the removal of summerfallow practices and the transition to continuous cropping land management practices.

The category with the most substantial literature is that of changes in land use. Much of the literature discusses the benefits from land use changes, especially in regard to increased SOM and SOC. Increasingly, there is confirmation that the adoption of GM crops is driving changes in land use, especially when it comes to the removal of tillage from crop rotations. The literature that exists is concentrated into agronomic aspects and the collection of data that quantifies the relationship. The only policy related evidence is an estimate of the impacts that would result if GM crops were to be removed from American farming practices.

Soil health improvements have a limited number of studies, but those that exist report soil health improves following the production of GM crops. Part of the literature on soil health relates to improvements in biodiversity, concluding that the impact agriculture has on biodiversity has been reduced following the adoption of GM crops.

4. Analysis of Evaluation Methodology

The practice of evaluations such as this have become more standardized and normalized. The Maryland Scientific Methods Scale (MSMS), which was developed in the 1970s to communicate to scholars, policymakers and practitioners in the simplest possible way the methodological quality of various evaluative studies, by coding them by their methodological quality. Using the approach developed by Ratcliffe (2019), which offers a fine-grained hierarchy for evidence, ranging from ad hoc confirmatory efforts (level zero) through to well-structured systematic reviews, which at their apex involve meta analyses of a population of repeated randomized controlled experiments. This second phase 2 of the analysis, compliments the robustness of the evidence identified in Section 2. This analysis quantifies which literature has theory, methods and evidence, or components of these three metrics. Quantifying the size of the evidence pool, allows for differentiation between where there are a few, disconnected studies showing benefits versus where there is a defined body of evidence firmly supporting benefits. The various levels of evidence include:

- Level 0: Those reviews that are confirmatory have limited value by themselves. Anecdotes, case studies and general reports that are designed to justify effort often have little probative value if they are the only evidence.
- Level 1: Two types of review fit here. Cross-sectional ex post comparison of treated groups with untreated groups or a before-and-after comparison of a treated group, without any comparison with an untreated group or any use of control variables. These types of analysis can identify correlations but often are not able to assign causality, partly because without any formally controlled counterfactual, there is no way to definitively show that the measure caused any observed results.
- Level 2: Studies at this level use control variables to do either cross sectional or before and after comparisons, albeit still without any untreated comparison groups. These types of studies may be able to establish a causal order but fail to rule out many threats to internal validity, in that there may be other explanations for what was observed.
- Level 3: The minimum standard for substantive evaluation is that the measure be structured as an experiment, with a well-defined source population that fits with the policy area, and where there are both treated and non-treated subjects that can be assessed for behavioral responses. In effect these could be considered a quasi-experiment or randomized control trial (RCT). Both causality and scale and scope of impact of the measure can be discerned in such studies.
- Level 4: This level of evidence draws on the repeated use of RCTs to control for other variables. This helps to remove the chance of spurious correlations from a single assessment of any venture.
- Level 5: Level 3 and 4 evidence is drawn from purposeful construction of in-experiment subjects and controls. Level 5 studies remove that restriction, applying the same experimental methods to randomly assigned populations, so that the causal assumptions can be validated more generally.

- Level 5*: Once a body of evidence through a range of Level 3 and 4 studies has accumulated, sometimes there is value in doing a study of studies, to discern the meta results and sensitivity analysis of the influence of different modeling approaches and assumptions on the derived outcomes.

We used this rubric to code all the literature, undertaking the following steps:

- In order to have a proper ordering, we rebased this MSI scale to 0 = 1, 1 = 2 and so on to 5* = 7.
- We first coded every article by its impact: area, chemicals, carbon sequestration, GHG, land use and soil health.
- We entered in their latest citation rate.
- Then we coded every article for where it would fit in the MSI scale, from 1-7.
- We then ran reports to understand the nature and quality of the work begin done.

Our assessment shows that this literature is still emerging (Table 3). We found 74 articles that offered evidence of environmental impacts. In a few cases the papers looked at more than one mechanism (agronomy, data, genetics, farm structure, machinery or policy) and a few explored more than one impact (area, carbon sequestration, chemicals, GHG, land use, soil health) and where appropriate they have been included more than once.

Table 3: Overview of the methods of evaluation

MSI coding	Count	Average citations	Average age of literature
1	4	42.5	16.5
2	25	103.4	10.9
3	21	129.3	9.1
4	10	163.5	11.2
5	5	77	7.0
6	0	na	na
7	9	547.5	11.8

One can see that some of the oldest work was really case study and anecdotal evidence (MSI 1) and that that work has a relatively low citation rate. Investigators have taken on more advanced methods (MSI 2-4) as the technology has matured and that body of work is getting taken up and cited. More advanced randomized control trials (RCTs) with counterfactuals (MSI 5) is just getting going. We found only five articles that on average were only seven years old and were relatively lightly cited. We could not find any that have run these studies long enough to qualify for

MSI 6, which requires repeated RCTs to remove sampling bias. We found a range of metal analyses, but one must keep in mind these surveys can only be as good as the underlying literature, which still lacks full rigorous RCTs.

Different impacts have been differentially studied. So far chemical, soil health and GHG effects are well articulated, albeit without repeated, full randomized control trials with confounding variables (which would code MSI = 6). Nevertheless, we found more than 10 articles in each area, and at least one meta-study in each domain (Table 4). We found fewer articles about carbon sequestration but we found more somewhat more rigorous methodology and at least one meta-study (MSI = 7). Relatively speaking the literature on area and land use is a bit weaker in terms of method, without any full randomized controls or meta studies. On average, the literature is 11 years old, with the oldest dating back to 2000. Apart from the impact on area, most of the literature is distributed around the mean of 11 years.

Table 4: Citation analysis

	Area	**Chemicals**	**Carbon sequestration**	**GHG**	**Land Use**	**Soil health**
# articles found	5	32	7	12	7	13
Average age (yrs)	8	11	11	10	12	11
MSI scale						
Lowest	2	1	2	2	1	1
Highest	4	7	7	7	4	7
Average rating	2.8	3.2	3.6	3.8	2.7	3.6
Citations						
Min		0	3	0	24	11
Max		7,430	2,582	281	626	452
Average	79	369	454	65	163	104
Average/year	8	26	25	6	13	10
Average to average/year	10	14	18	10	13	11
Average cites/year per MSI point	2.9	8.0	7.0	1.7	2.9	2.9

Comparing citations tells us something about the maturity of the literature. All other things being equal, more highly cited articles are generally recognized as providing more value. Successive comparisons offer some insights. There is both absolutely more literature on the chemical impacts:

the total citations are higher, the average cites per year (adjusting for the age of the literature) is almost at the top and the average cites per year per MSI point is strong.

Carbon sequestration, GHG, land use and soil health all have some strengths, but the literature is a bit thin, which suggests one should be cautious about making judgements on its messages. By definition repetition is necessary to confirm the impacts.

5. Conclusion

The objective of this report is to provide a summary of peer-reviewed literature for articles that provide evidence that innovations in plant breeding technologies and crop protection products, including biologicals, have contributed, or are contributing to climate change mitigation and adaption. The review shows how several factors are working in concert to create significant climate change impacts: development of different GM traits; trait deployment in the most significant commodity crops; widespread adoption of GM crops globally; and consequent beneficial changes in farming practices. In aggregate, the literature discloses a strong trend in the accumulation of reinforcing evidence that new technologies, especially GM crops, play a significant role in climate change mitigation and adaptation. This trend is expected to continue, and will be reinforced, as new technological introductions further reshape agriculture.

Although the evidence base reported here is compelling and increasing, the literature itself is evolving. Qualitative improvements in research methodologies documenting the impact of GM crops on climate change mitigation and adaptation are anticipated as new evaluation and measurement techniques are developed. As more scrutiny is applied on different economic sectors' ability to contribute to climate change initiatives, agricultural production will be expected to make productivity gains while lowering environmental impact. Better study methodologies will be called upon to provide accurate and replicable data to support mitigation and adaption policy frameworks. In these frameworks, one can expect much greater pressure on agriculture to demonstrate its current and future ability to contribute meaningfully to climate change adaptation and mitigation.

This report summarizes the quantified field level and system level impacts of agricultural innovations and their effects on climate change. As identified above, this is a small body of literature. However, there is an abundance of literature involving innovations in many of these areas, as well as innovations in inoculants, biologics and other crop, chemical and fertilizer innovations, that reports on results from in vitro, laboratory or confined experimental trials. This literature provides the scientific validation of these innovations and further research will be required to undertake commercial field production assessments capable of measuring the relationship with adaptation to, or mitigation of, climate change.

Virtually all of the literature identified in this report deals with the mitigation of climate change. Literature on adaptation to climate change is less available. However, much of this can be explained by author preferences to use mitigation as a key word, when in reality, the article deals with adaptation. The evidence on reduced tillage and increased carbon sequestration is the result of farmers adapting to changing climates. Articles that highlight the long-term beneficial effects of GM crop adoption are ultimately about adaptation to climate change, as farmers continue to use innovative technologies that allow them to ensure higher yields and hence profitability. Innovative agricultural innovations may initially be adopted in an effort to mitigate climate change, but long-term use (a decade or longer) indicates that the adopters have adapted to climate change.

The following key points can be summarized from the findings of this report.

1. Without the innovations provided by GM crops, chemicals and fertilizer, more land would be required to produce current food volumes. At a minimum, 10% more land would be required. This additional crop production land would need to come from reducing wetlands, deforestation or conversion of environmentally sensitive land.
2. Innovations in seed technology, like herbicide tolerance and improved weed control, has resulted in over 300 million tonnes of CO_2 sequestration from reductions in tillage, over the past 25 years.
3. The development and increasing commercialization of herbicide tolerant and insect resistant crops has reduced the amount of chemical applied for weed and insect control in the vast majority of studies. Importantly, in additional to reductions in chemical use, is the parallel reductions in the environmental impact from fewer chemical applications, reaching up to 50% in some crops.
4. Increases in soil carbon storage are the result of a systems approach to improved sustainability, not a single innovation. The development of improved traits through biotechnology (i.e., herbicide tolerant, insect resistant, drought tolerant) greatly contributes to reductions in both abiotic and biotic stresses, allowing for continuous crop production without the use of tillage.

The ability to consistently keep tillage out of land management systems, facilitates long-term carbon storage.

5. Reductions in the use of tillage, has substantial environmental benefits regarding changing climates, in that the continual removal of tillage decreases erosion, reduces the presence of chemical residues and fertilizers in watersheds. Additionally, moisture conservation is increased, allowing plant to sequester great amounts of carbon during drought years.

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