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REVIEW ARTICLE

Sustainability Benefits Following the Adoption of Genetically Modified Crops in Canada

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Abstract

The adoption of genetically modified canola in 1995 in Western Canada was done to improve the control of weeds during crop production. Thirty years later, Western Canadian agriculture has witnessed a complete transformation, whereby the use of summerfallow as the leading form of weed control has virtually disappeared, to be replaced by continuous cropping, zero or minimum tillage land management practices. Of course there are trade-offs. The removal of tillage practices has increased soil moisture conservation and reduced soil erosion, but it has also resulted in an increase in herbicide applications. However, the environmental impact from the current suite of herbicides applied are considerably lower than previous ones, which often required soil incorporation instead of foliar application. All food production practices have impacts on the environment and biodiversity, however, the key is to identify best practices that contribute to increased production coupled with a lower environmental footprint. This article reviews the transition that Western Canadian agriculture has undergone over the past 30 years, highlighting the benefits for the environment and biodiversity.

Keywords: Biodiversity, Genetically modified crops, Innovation, Regulation, Tillage

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Introduction

Effective weed control is a leading factor in crop yield maximization. Inefficient weed control enables weeds to use scarce soil moisture and nutrients, rather than these being available for the seeded crop. The high rate of seed production by weeds results in a compounding of the problem from one year to the next, if improperly controlled. For example, striga is an extremely noxious weed in Africa and if not properly controlled can result in yield losses of 100% (Benjamin *et al*., 2024). The lost yield has significant economic impacts, with one estimate indicating that parasitic weeds in Africa account for economic losses of US$200 million per year, increasing at a rate of US$30 million per year (Rodenburg *et al.,* 2016). Yield losses from ineffective weed control exist across all crop kinds, as research from India found yield losses of up to 76% for soybeans, 71% for groundnut, 66% for rice, and 65% for corn (Gharde *et al*., 2018).

The inability to efficiently control weeds in dryland Canadian Prairie agriculture can reduce wheat yields by up to 20% (Flessner *et al*., 2021) and canola yields by up to 40% (Harker, 2001). Greater yield variability resulting from higher weed populations can reduce yields to the point that the crop is no longer profitable. Weeds propagate at far higher rates than domesticated crops, as a high-yielding wheat variety is capable of producing 40-50 seeds per plant, while palmer amaranth, for example, can produce at least 100,000 seeds per plant (Grain Farmers of Ontario 2025). Kochia is a noxious weed commonly found in the Prairies, which is capable of producing up to 25,000 seeds per plant per year (Government of Manitoba, no date). Given the dramatically higher seed production, inefficient weed control not only has adverse economic impacts during the growing season, but also spills over and further impacts subsequent crops. Early germinating weeds are capable of growing rapidly and providing a canopy that shields seeded crops from sunlight, resulting in minimal or even no crop production within weedy areas of crop land.

Tillage has historically been used to control weeds in virtually all crop-producing regions. Adverse impacts of tillage use are increased soil erosion and reduced moisture conservation. The decade of the 1930s witnessed millions of tons of topsoil erosion due to the prolonged drought and consistent tillage practices across the major crop-producing regions of both Canada and the United States. The 1980s were a similar decade of below average precipitation, resulting in further soil erosion in these regions. During this decade, farmers and industry increasingly realized practices needed to change to ensure the future sustainability of crop production. Equipment innovations enabled greater adoption of direct seeding practices, reducing the need for tillage as farmers began to transition tillage out of their land management practices.

A parallel innovation that complemented the removal of tillage from land management practices was the commercialization and adoption of genetically modified (GM) and mutagenic herbicide-tolerant (HT) canola varieties, beginning in the mid-1990s. In-crop herbicides before this time provided limited weed control, especially for broad-leaf weeds and thistles. The initial GM canola varieties that were glyphosate and glufosinate-tolerant provided consistent year-over-year effective weed control that farmers required to completely remove tillage as the leading form of weed control. As a result, the adoption of GMHT canola became the most rapidly adopted innovation in the history of Canadian Prairie agricultural production.

This article provides a review of crop production practices in the Canadian Prairies before the commercialization of HT crops in 1995 and in the subsequent 30 years. It highlights how improving the efficiency of weed control has driven the improved sustainability of agriculture across the crop-producing regions of Western Canada.

Crop Production Practices Prior to GM Crop Adoption

Following the settlement of the three Prairie provinces of Alberta, Saskatchewan, and Manitoba in the latter half of the 19th century, weed control quickly became of key importance. This issue quickly arose as many of the weeds that had affected crop production in Europe were transported to this region via seed shipments that settlers brought with them. The result was that within several years of land being broken for crop production, weeds began to establish and negatively affect yields. Weed control was achieved through the use of summerfallow, which is a process whereby a field is left fallow for an entire growing season and routinely tilled to prevent weed growth. The number of required tillage passes was dependent on the amount of rainfall in the region, as in some years, only 2-3 tillage passes would be required, while in others, as many as 10 may have been needed. Fig. 1 illustrates the total summerfallow area for the three Prairie provinces, which peaked in 1970 at 14.9 million hectares (36.8 million acres) and has consistently declined to 600,000 ha in 2023 (1.5 million acres).

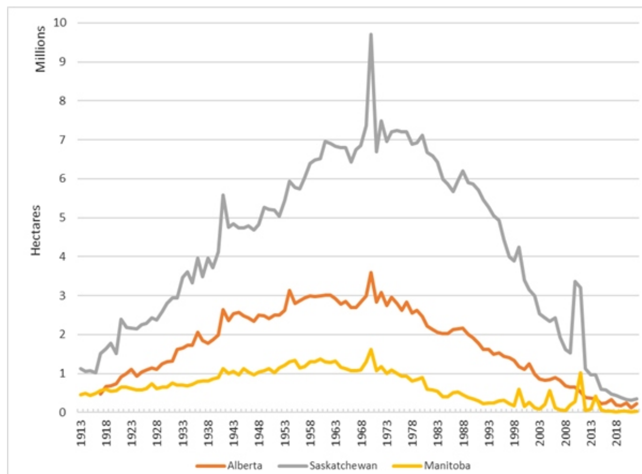

Fig. 1: Canadian Prairie summer fallow acreage, 1913-2022.
Source: Statistics Canada, 2023.

Given the importance of summerfallow for efficient weed control in the 20th century, many parts of the Canadian Prairies had two-year crop rotations that consisted of wheat one year and summerfallow the next. In areas with greater livestock densities, three-year rotations were common, where wheat would be grown for cash sales on summerfallow, followed by a crop used for forage purposes, such as oats, barley, or clover. The third year would be summerfallow. Crop diversity was limited, as there were few legume varieties developed for Prairie production, other than forage varieties as part of livestock nutritional needs. Many farms only produced wheat, as it was the most highly priced cereal crop, and if a farm was strictly involved in grain production, other cereal crops had lower economic value. With the introduction of rapeseed varieties in the 1950s and the initial pea varieties in the 1970s, crop diversity slowly began to increase.

Near the end of the 20th century, a lengthy period of drought impacted this region, reducing yields for most of the 1980s. During this drought period, it became increasingly apparent for the need to change land management practices as topsoil was frequently being blown away from summerfallow fields. During this period, on windy days, the sky would be filled with dirt and ditches were often filled with blown dirt.

Innovative farmers and short-line equipment manufacturers began to experiment with new seeding technologies, such as those that no longer turned the soil over, such as with diskers, but rather used a chisel to create a furrow for seed placement, leaving the soil untilled. While some experimenting initiated in the late 1960s, this expanded in the 1970s and by the 1980s, manufacturing of direct seeding implements was occurring. The increased adoption of zero tillage and minimum tillage equipment throughout this period were contributing factor to the reduction in summerfallow acreage in Fig. 1.

There have been some periodic increases in the use of tillage, especially in years with higher snowfall and spring precipitation, as farmers will use tillage as part of the efforts to dry soils down to the point that they can be seeded. Additionally, the province of Manitoba typically receives higher precipitation than the other two provinces, which contributes to explaining the higher rate of summerfallow variability, as it is not uncommon that land is too wet to seed in the spring, forcing farmers to summerfallow unseeded fields to control weeds.

The high utilization of tillage reduced the potential for improved biodiversity, given that fields were routinely tilled to ensure weeds were not growing, thereby depriving many populations of sufficient feed sources, not to mention protection from ground cover. The consistent tillage passes over summerfallow fields additionally contributed to reduced biodiversity in crop fields, especially during summerfallow years.

Coming out of the 1980s, Prairie agriculture had been adversely affected by the decade-long drought. Drought, combined with high winds, once again created significant soil erosion problems. Many farmers realized that changes would be required to ensure the long-term sustainability of their land. This realization improved farmers' willingness to approach innovative technologies with a more positive approach than may previously have been the case, as without new products and technology, things would not improve. Land management changes were occurring across the Prairies during the 1980s, which would only increase in the subsequent decades.

Crop Production Practices Following GM Crop Adoption

The final handful of years of the 20th century witnessed one of the most significant innovations in the history of crop agriculture, the commercialization of genetically modified herbicide-tolerant (GMHT) crop, namely canola, corn, cotton and soy, although in the 1990s, only GMHT canola was grown in the Prairies. The potential to efficiently control weeds in crops now existed, resulting in a transition in land management practices as the use of summerfallow to control weeds consistently declined following the commercialization of GMHT canola in 1995. Over the ensuing decade, summerfallow acreages decreased as crop production became a continuous process, frequently involving the use of zero tillage or minimum tillage land management systems.

As identified above, efficient weed control is a key factor towards ensuring that yields are as high as can be possible. Given the lack of efficient in-crop herbicides to control weeds, the historically leading method for efficient weed control was through the practice of summerfallow. The commercialization of GMHT crops, but GM canola in particular, in 1995, provided a new option for efficient weed control. The first two GM canola varieties that were commercialized were Monsanto's (now Bayer) glyphosate-tolerant canola and Agrevo's (now Bayer) glufosinate-tolerant canola. Pioneer Hi-Bred also had a variety of imidazolinone-tolerant canola commercialized in 1995. Following the risk assessment of HT canola varieties by the Canadian Food Inspection Agency (CFIA), these varieties entered a two-year seed multiplication program, consisting of 30,000 acres in 1995 and 230,000 acres in 1996 (Smyth and Phillips, 2001).

Initial farm level adoption occurred in 1997, with virtually full adoption within 15 years (Fig. 2). This is considerably faster than the average length of time for peak adoption, which is estimated to be 22-23 years in length (Alston and Pardey, 2021). By the third planting season in 1999, over 50% of seeded acres were done with HT varieties. By 2004, adoption reached 75% and by 2009 was estimated to be 91%. The adoption rate of HT canola varieties represents the most rapid adoption of any agricultural technology in the history of Canadian agriculture. This rapid rate of adoption indicates that farmers experienced efficient and economic weed control by adopting HT canola varieties. There is virtually no non-HT canola currently produced.

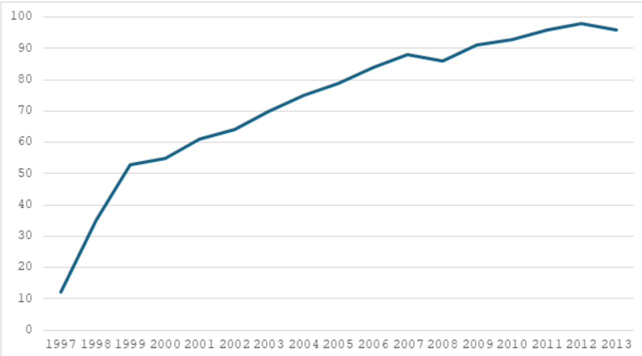

Fig. 2: Canadian HT canola adoption rates, 1997-2013 (seeded acres percentage).
Source: Canola Council of Canada (no date).

With the 2026 crop year representing the 30th year of commercial HT canola production in the Canadian Prairies, significant additional benefits have been realized. With the rapid adoption of HT canola in the decade from 1997-2007, this corresponds to the significant decline in crop summerfallow acres in Fig. 1. In Saskatchewan alone, summerfallow dropped from 4 million hectares to less than 400,000, a decrease of over 90%. The effective weed control provided by HT crops enabled farmers to remove summerfallow from their crop rotations. This has resulted in many fields across the Canadian Prairies being in zero tillage or minimum tillage practices for 20 years or even longer with some of the earliest adopters. The contrast in the use of tillage between crop-producing regions that adopted HT crop technology compared to those that failed to do so is starkly evident in Fig. 3. Europe rejected GM crop technologies, with only Spain and Portugal producing small acre ages of GM corn. The remainder of Europe's crop-producing regions rely on older, more environmentally impactful pesticides as well as tillage for weed control options.

The results of a farmer survey following a decade of HT crop production identified substantial environmental benefits, with 86% of respondents indicating they had experienced reduced soil erosion and 83% reporting higher levels of soil moisture conservation (Smyth *et al.,* 2011a). Further benefits were identified through the reduction in the environmental

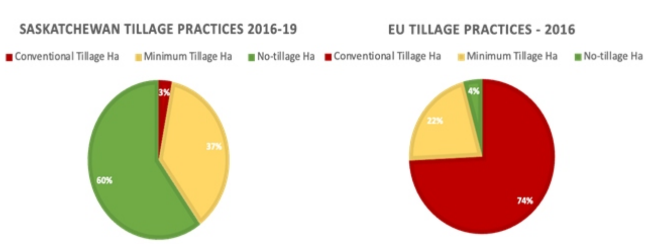

Fig. 3: Comparison of tillage rates between Canada and Europe.
Source: EuroStat (2016); Sutherland *et al.,* (2021).

impacts of canola in-crop herbicides applied. Before the commercialization of HT canola varieties, there were very limited options for in-crop herbicide controls, resulting in many herbicides having to be soil incorporated before, or in conjunction with, seeding. The transition to effective in-crop foliar-applied herbicides reduced the environmental impact of herbicides, with the environmental impact of the top five herbicides applied to canola production dropping by 53% between 1995 and 2006 (Smyth *et al*., 2011b). A key reason for the decline in the environmental impact of canola herbicide use was the drop in the volume of herbicide active ingredient needing to be applied, which dropped from 648 grams per hectare to 401 grams per hectare, a 38% reduction. Between 1995 and 2006, this represented a reduction in the volume of herbicide active ingredient being applied to canola fields by an estimated 1.5 million kilograms.

The increase in canola acres is represented by the reduction in summerfallow acres. In 1995, the three Prairie provinces of Alberta, Saskatchewan and Manitoba had combined summerfallow acres of 13 million (Fig. 1). Between 1995 and 2025, seeded canola acres increased by 8.5 million acres (Fig. 4). The increased canola production did not displace other crop production; it replaced annual summerfallow acres.

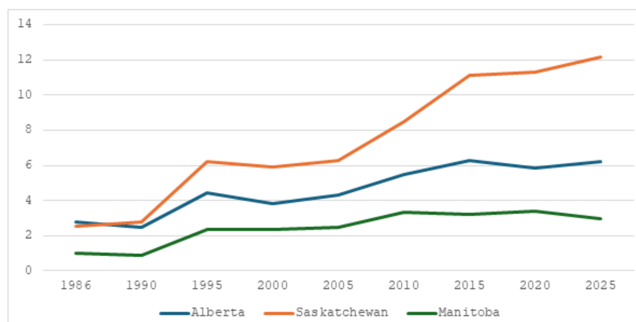

Fig. 4: Canadian Prairie seeded canola acres, 1986-2025 (millions of acres).
Source: Canola Council of Canada 2025.

A complement to the adoption of HT canola varieties was increased investment into the development of new pea and lentil varieties across the Prairies. This allowed farmers to increase the diversity of their crop rotations, which expanded to include alterations between cereals, pulses, and oilseeds. From 2000-2008, lentil production ranged from 1.3 to 2 million acres. This rose significantly over the subsequent decade, such that from 2020 to 2024, production increased to a range from 3.7 to 4.3 million acres (Sask Pulse, 2025). This increased crop type rotation diversity reflects a significant change from earlier decades, where rotations consisted of wheat and summerfallow.

Table 1: Change in average annual Saskatchewan fertilizer use, 1991-1994 to 2016-2019

Period	Crop yield (bu/ac)	Fertilizer applied (lbs/ac)	Fertilizer rate (lbs/bu)	Crop acres (millions)
1991-94	40	231	6	33.3
2016-19	51	467	9	40.5
Percent increase	28%	102%	50%	22%

Rotation diversity ensures that different herbicide modes of action are applied to fields, thereby contributing to ensuring that the development of herbicide resistance in weed populations is minimized, as this follows good agronomic practices.

The diversity in the number of crops in a rotation has impacted fertilizer use, with greater volumes being applied. This increase in applications has contributed to a corresponding yield increase. While fertilizer volumes have increased, the correct assessment is to determine how much crop is produced per pound of fertilizer applied, resulting in a fertilizer use efficiency calculation. Between the periods of 1991-1994 and 2016-2019, Saskatchewan farmers increased their average annual total fertilizer application by 102% (Table 1). This suggests that for every 1% increase in fertilizer application, there is a corresponding 0.87% increase in crop yields. From 1991-1994 to 2016-2019, Saskatchewan farmers converted 7.2 million acres of summerfallow to continuous crop production, thereby increasing the overall fertilizer use, as summerfallow production does not require the use of fertilizers. This conversion accounts for 44% of the increase in fertilizer usage. Additionally, there was a shift in fertilizer application timing, particularly due to advances in equipment and technology that allow for in-crop fertilizer applications. In the 1991-1994 period, no in-crop fertilizer applications were made, while during the 2016-2019 period, 13% of total fertilizer applications were made in-crop (Lika *et al*., 2024a). This advancement resulted in less post-harvest fertilizer application, which can be susceptible to spring melting and run-off, whereby nutrients are unintentionally transferred to watersheds.

The increased crop rotation diversity and the resulting alternating herbicide modes of action have made a significant contribution to lowering the development of herbicide resistance (HR) in new weeds. In the period from 1988-1995, an average of 2.5 new HR weeds were reported each year. The adoption of HT crops has contributed to a reduction in the reporting of new HR weeds, as the rate of reporting across the Canadian Prairies has continually dropped. As farmers learned how to best integrate HT crops into their rotations, the rate of new HR weed reporting dropped precipitously. Between 2016 and 2021, only three new HR weeds were reported in all of the Canadian Prairies (Sutherland *et al*., 2025). This drop in the development of new HR weeds has been driven by increased crop rotation diversity as the number of farmers practising at least three crops in their rotation increased from 59% from 1991-1995 to 80% from 2016-2019, while the percentage of farmers practicing two-year rotations decreased from 39 to 2% over the same period (Sutherland *et al*., 2025).

The transition in land management practices away from rotations that relied on tillage as the leading form of weed control to continuous cropping involving HT crops in the rotation has transitioned crop land from being a carbon emitter to a sequesterer. Summerfallow practices required frequent passes during the growing season to ensure efficient weed control, with the total number of passes varying by region and precipitation levels. Each tillage pass released carbon into the atmosphere, resulting in higher amounts of carbon released during the summerfallow year than was sequestered during the crop year. It is estimated that the reliance on tillage by farmers in Saskatchewan from 1991 to 1994 resulted in a 1,000-hectare farm releasing 33.4 mg of soil organic carbon (SOC) annually, while storing 16.7 Mg of SOC from crop production. By the 2016 to 2019 period, the same 1,000-hectare farm would have sequestered 119 Mg of SOC annually, in addition to a further reduction of 421 Mg of SOC due to the reduction in summerfallow practices (Sutherland *et al*., 2021). If the change in emissions was compared to the average emission of an automobile, a 1,000-hectare farm from 1991-95 would have released 15 times more carbon than an average automobile per year, and by the 2016-2019 period, it would have sequestered the equivalent emissions from 95 cars.

With crop land being in minimum or zero tillage land management practices for 20 years or even longer, farmers are experiencing increases in soil health. While many farmer observations are challenging to quantify, such as reduced soil erosion following substantial rainfall, it is possible to quantify changes in soil organic matter. Soil testing is a common practice in Prairie crop land, as it measures the level of soil nutrients available in a specific field each fall, providing farmers with greater knowledge about crop nutrient requirements for the subsequent crop year. A standard part of each soil test is to report the level of soil organic matter. Research on changes in soil organic matter levels in Saskatchewan identified that soil organic matter levels increased 41% between the periods of 1990-1999 and 2015-2024 (Sutherland *et al*., forthcoming). Increases in soil organic matter were reported across all of the major soil zone classifications in the province.

The above confirmation of changes in land management and weed management practices dating back to the early 1990s confirms the substantial impacts of agricultural innovations. The combination of improved crop genetics, such as HT crops and nitrogen-fixing pulse crops, the adoption of more benign crop pesticides–especially herbicides, and equipment advances enabling minimum and zero tillage land management practices all combine to create a system of sustainable crop production. While those critical of modern crop production practices suggest that continuous cropping and the resulting increase in pesticide applications are a detriment, the evidence from 30 years of HT crop production as part of a crop rotation soundly rejects this argument.

Benefits for Biodiversity

One of the leading debates regarding the transition away from utilizing tillage as the leading form of weed control to diverse, but constant, crop production, which relies on pesticides to control production threats, such as plant diseases, insects, and weeds. The total volume of pesticide active ingredient applied has increased due to the millions of additional crop acres that are presently part of crop rotations, as compared to crop rotations that relied on summerfallow for weed control. Even though more crop acres are planted each year, and more pesticides are applied, the environmental impact of those being applied is frequently lower. Comparing the in-crop herbicides applied to Saskatchewan crops between the periods of 1991-1994 and 2016-2019 identified that the environmental impact of those applied was 65% lower, while 45% less herbicide active ingredient was applied per acre (Lika *et al*., 2024b). The decline in the environmental impacts of the herbicides being applied contributes to mitigating impacts on non-target organisms.

One of the most significant changes for biodiversity has been the transition to continuous plant matter in fields. When rotations were predominantly wheat followed by summerfallow, the field was barren soil every other year, limiting biodiversity as there was no ground or crop cover for many species. Summerfallow fields consisted of black dirt, which was highly susceptible to wind and water erosion. Constant crop cover provides increased habitats for beneficial insects, including pollinators, as well as ground-nesting birds.

Assessing pollinator populations, especially wild populations, is extremely challenging, such that few studies exist. One metric that is used to assess pollinator populations is the number of honey bee hives. Even though these hives are managed, they are subject to the full array of population stressors, such as diseases, mites, land use change, and pesticides. While total crop acres have increased over the past 35 years, resulting in larger volumes of pesticide active ingredient being applied, the environmental impacts of the increased applications are lower, resulting in increased honey bee hives across Canada (Fig. 5). The number of honey bee hives has increased by 14% over the 12 years from 2012-2024.

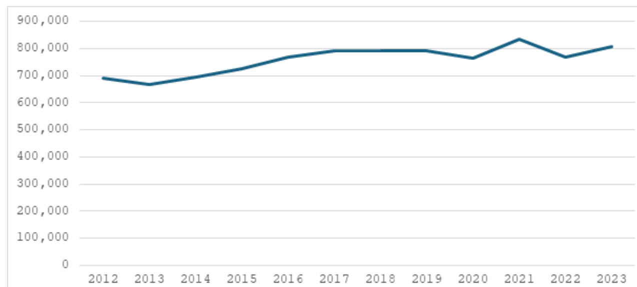

Fig. 5: Honey bee colonies in Canada, 2012-2024.
Source: Government of Canada 2025.

There are additional uncorroborated reports from farmers at public events that they believe there has been an improvement in biodiversity following the removal of tillage as the leading form of weed control. As the increase in soil organic matter has been quantified, farmers indicate there has also been a corresponding reduction in soil compaction due to increases in earthworm populations. While this has not been confirmed through peer-reviewed analysis, it is a form of citizen science engagement, whereby farmers provide valued insights into field-level changes occurring on their farms over time.

Agriculture and the production of food will always have impacts on biodiversity. The only way for agriculture and food production not to have an impact on biodiversity would be to stop food production entirely. This is not a realistic option, so the challenge becomes how to reduce the biodiversity impacts of agriculture and food production as much as is reasonably possible, without adversely impacting the overall amount of food produced. Research indicates that the adoption of GM crops contributes to reducing the impacts of crop agriculture on biodiversity (Carpenter, 2011). Farmers across the Prairies have substantially adopted HT canola, the majority of which is GM; however, all HT canola production provides biodiversity benefits. The ability of farmers to adopt production practices that include continuous cropping and zero tillage or minimum tillage ensures that the environmental impacts of these practices have been substantially reduced, thereby providing biodiversity benefits.

Summary

Over the past 30 years, agriculture in Canada has consistently demonstrated advances in sustainable production practices, as well as in mitigating impacts on biodiversity. This achievement has been possible due to significant and consistent investments into research and development (R&D) of new products and technologies that have driven these advances. Increases in sustainable agricultural practices and reduced biodiversity impacts are only possible from sustained R&D investments; they are not possible by returning to historic crop production, as these varieties are more susceptible to insect, weed, and disease pest pressures, which results in lower yields, as well as resulting in greater environmental and biodiversity impacts due to the application of older, more toxic pesticides.

Crop production in the Canadian Prairies has aptly demonstrated the value of investing in new agricultural products and technologies. Research into the initial application of genetically modified technology began in the mid to late 1980s. A decade of this research resulted in the initial commercialization of GM crops in the mid-1990s. This region is now globally recognized as among the most sustainable producers of crops (Bamber *et al*., 2025). As the sustainability of crop production increases, the biodiversity benefits are correspondingly enhanced through innovations such as more efficient fertilizer applications, application of pesticides with lower environmental impacts, and the removal of summerfallow practices from land management systems. However, this would not have been achieved were it not for the 40 years of innovation investments and 30 years of commercial production.

A significant challenge for agriculture, especially regarding contributing to meeting international climate change commitments, is how to contribute to meeting these objectives in the face of increased pressure from environmental organizations focused on preventing the integration of innovative strategies into domestic policy and funding frameworks. The cornerstone of international sustainability principles is to produce more food per acre of land, while reducing the level of inputs required, as well as reducing the land area for food production. This triple challenge will be impossible to meet without dramatic advancements in innovative products and technologies.

As has been empirically established in the Canadian Prairie regions, the adoption of GM crops, especially those that are herbicide-tolerant, is the driving force of sustainability advances and a mitigation of the factors that can be stressors to biodiversity. This has been confirmed with 91% of Saskatchewan farmers indicating that the use of glyphosate is the number one factor for their ability to increase the utilization of sustainable land management practices in their crop rotations (Sutherland *et al*., 2021). The evidence clearly supports the tremendous advantages of the removal of tillage as a land management practice and how this is correlated to crop-producing regions that have a lengthy history of HT crop adoption and production. Improving soil health is an important factor for all farmers, and 30 years of HT crop production in the Canadian Prairies has demonstrated increased levels of soil organic matter, a key component of healthy soil definitions. This improvement would not have been possible were it not for the efficient weed control provided by HT crops, enabling the permanent removal of tillage practices.

As international climate agreements and bioeconomy frameworks become further integrated into domestic policies for agriculture and environment, evidence is going to be required to provide the basis for policy. While many activist environmental groups have invested massive fiscal resources in the creation and dissemination of false information regarding the safety and benefits of HT crops and biotechnology (Ryan *et al*., 2020), the evidence from adopting farms and countries overwhelmingly refutes these activist claims. While there is a small but increasing component of research confirming the benefits of GM crops towards mitigating the effects of climate change, more research is required (Smyth *et al*., 2024). The quantification of increased sustainable agriculture following the adoption of biotechnology and HT crops is in its infancy, and research into the impacts on biodiversity is very scant. Research in these fields is important to inform policymakers in non-GM crop adopting countries that the adoption of these sustainable crops provides a wide range of benefits in terms of increased crop and food production, as well as in reducing agriculture's environmental footprint. It is research of this type that is more important than ever, as if countries are going to be able to make domestic sustainability improvements, which can potentially reduce the impacts of agriculture and food production on biodiversity, greater adoption rates of GM crop and gene editing technologies will need to happen.

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