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Quantifying changes in the environmental impact of in-crop herbicide use in Saskatchewan, Canada

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Abstract

The sustainable management of herbicides is critical to modern agriculture and the environment. This article examines the evolution and environmental implications of herbicide use in Saskatchewan, Canada, agriculture. It quantifies changes in herbicide use and their environmental impacts by analyzing farm-level herbicide use data from 1991 to 1994 and from 2016 to 2019 through the environmental impact quotient. Results confirm significant reductions in both environmental and toxicological impacts of herbicides used, underlining the pivotal shift from tillage-based weed control to herbicide-resistant cropping systems. The environmental impact of the top five herbicides (glufosinate, glyphosate, clethodim, imazamox, and 2,4-D) used from 2016 to 2019 is 65% lower than that for those herbicides (MCPA, 2,4-D, bromoxynil, diclofop-methyl, and trifluralin) used from 1991 to 1994, with a 45% reduction in the active ingredient applied per acre. Despite increased herbicide use due to more crop acres being seeded, the findings highlight a marked improvement in the sustainability of herbicide use, affirming the importance of technological advancements in agriculture. This research contributes valuable insights into long-term trends in herbicide use, offering a practical framework for informed decisions aligning with sustainable agricultural practices as well as reduced biodiversity impacts.

Introduction

The sustainability of chemical applications is a topic of ongoing debate in agricultural and environmental policy discussions for many governments. All chemicals, including herbicides, insecticides, and fungicides, are important technologies in farmers' tool kits and are an integral part of sustainable crop management and production systems. However, their use is often misunderstood, and uncertainty among the public can result in distrust of technology (Allum et al. 2008; Sutherland et al. 2020). Few sustainable, alternative weed control options to herbicide use are currently available to farmers. Thirty years ago, summer fallow was a common practice, and conventional tillage was the leading form of weed control before planting. Both practices contributed to decreased soil quality and moisture levels (Awada et al. 2014) and increased soil erosion (Rust and Williams, n.d.; Verity and Anderson 2011), which resulted in some chemicals and fertilizers leaching into local watersheds.

Reductions in summer fallow acres and tillage applications align with global sustainable practices, contributing to improved soil health, moisture conservation, and carbon sequestration (FAO 2023; Lal et al. 2007). The adoption of conservation tillage, as seen in Saskatchewan, corroborates these improvements (AAFC 2022; Derpsch et al. 2010; Hobbs et al. 2008; Sutherland et al. 2021). This research focuses on the region's herbicide use evolution, particularly through the environmental impact quotient (EIQ), to assess the environmental impact of these changes.

The controversy surrounding the use of glyphosate, evident in various restrictions, illustrates the complex balance between agricultural productivity and environmental stewardship (Cerdeira and Duke 2010; Duke and Powles 2008; Health Canada 2019; Kynetec 2022; Marambe and Herath 2020; PMRA 2017; Wisner Baum 2022). However, this article's primary focus is not on individual herbicides but on the broader trends in herbicide use in Saskatchewan, particularly between 1991 to 1994 and 2016 to 2019. Between these periods, a significant increase in seeded acreage and a decrease in summer fallow was observed (Statistics Canada 2023), along with low potential risks from herbicide use (AAFC 2022).

This research extends to the period of herbicide-resistant cropping systems' introduction, which marked a significant shift from tillage-based weed control to more sustainable practices. The transition to herbicide-resistant crops, such as canola (*Brassica napus* L.), has been integral to enhancing carbon sequestration in agricultural soils (Sutherland et al. 2021; West and Post 2002) and reducing the need for multiple herbicide mixtures (Helling 2005; Sikkema and Robinson 2005; Van Acker et al. 2017). This shift reflects reduced tillage, preserving soil structure and organic content, and highlights a significant improvement in the sustainability of herbicide use.

In Saskatchewan, canola, with its various herbicide-resistant traits, including genetically modified (GM) glyphosate- and glufosinate-resistant and mutagenic imidazoline-resistant varieties, represents a significant shift in agricultural practices (Smyth et al. 2011). GM crops are plants whose DNA has been altered using genetic engineering methods to introduce traits like increased resistance to pests or herbicides (Turnbull et al. 2021). The increasing reliance on herbicides in Canadian agriculture, with a pronounced increase in cropland treated with herbicides from 1981 to 2016, is particularly notable in the prairie region (Malaj et al. 2020). However, this increase has been accompanied by notable changes in herbicide use efficiency and environmental impact. For instance, a 42.8% decrease in total herbicide use per hectare in canola, particularly in herbicide-resistant varieties, was observed between 1995 and 2000 (Brimner et al. 2005), reflecting a trend toward more sustainable use patterns.

Studies like MacWilliam et al. (2016) and Brookes and Barfoot (2017) emphasize the significant reduction in herbicide use per metric ton of canola produced and the global environmental benefits of GM crops, respectively. These findings align with the regional trends observed in this research, demonstrating reduced environmental and toxicological impacts of herbicides used in Saskatchewan. This reduction is further evidenced by the decline in herbicide active ingredient (AI) applied to canola in Canada between 1995 and 2006, indicating improved environmental sustainability (Smyth et al. 2011).

While herbicide-resistant weeds date back to the 1950s in Canada, the environmental impact of herbicide use extends beyond their immediate application, as continuous cropping rotations require greater awareness of chemical variation as part of the strategy to minimize the potential for herbicide-resistant weeds to evolve. The emergence of glyphosate-resistant weeds necessitates integrated weed management strategies (Beckie et al. 2014), while studies on herbicide persistence and mobility offer insights into their long-term ecological impacts (Helling 2005). Furthermore, international perspectives, such as the use of atrazine, provide a comparative context for understanding herbicide impacts. Recent studies, including those by Gagneten et al. (2023), emphasize the nuanced ecological consequences of atrazine in diverse environments, offering a broader comparative framework that enriches our understanding of its global impact (Hayes et al. 2011; de Souza et al. 2022).

The evolving dynamics of agricultural practices, particularly in the context of modern herbicide use, are crucial given the increasing scrutiny and regulatory actions of herbicides. The European Union's Farm to Fork Strategy illustrates these global policy shifts with its ambitious targets for chemical reduction (FAO 2023). Meanwhile, in Canada, regulatory reviews like the Pest Management Regulatory Agency's reassessment of glyphosate (Health Canada 2019) reflect the ongoing scientific balance between agricultural productivity and environmental sustainability.

Saskatchewan's experience as a significant agricultural producer highlights the importance of understanding the environmental impact of herbicides within the broader Canadian agricultural policy framework. This article's focus on quantifying the changes in in-crop herbicide use and their environmental impacts in Saskatchewan offers valuable insights for informed decision-making, aligning with sustainable agricultural practices.

Materials and Methods

This research aims to calculate the field use environmental impact quotient (EIQ-FU) for herbicides used postemergence in the crop rotation periods of 1991 to 1994 and 2016 to 2019. The EIQ, a comprehensive tool developed by Kovach et al. (1992), evaluates the environmental impacts of pesticides. It encompasses three key components: farmworker impact, consumer impact, and ecological impact. These components account for the direct and indirect effects of pesticide use on human health and the environment. The farmworker component considers factors like dermal and respiratory exposure, while the consumer component assesses the potential impact of pesticide residues on food. The ecological component evaluates the broader environmental consequences, including effects on nontarget species and ecosystems (Eshenaur et al., n.d.).

Each component of the EIQ is quantified by considering various subcomponents, such as acute and chronic toxicity, and rates of dispersion and degradation in the environment. These subcomponents reflect a range of factors influencing pesticide toxicity and exposure levels, providing a nuanced approach to assessing environmental and health impacts. The combined scores of these components yield the overall EIQ-FU value, which offers a comparative measure of the potential environmental impact of different pesticides.

Although the EIQ-FU provides valuable insights into the environmental footprint of pesticide use, it is important to recognize its limitations. One of these is the potential oversimplification of complex environmental dynamics. The EIQ formula (Grant, n.d.) generally does not account for the development of pest resistance, which is a significant factor in long-term pesticide management and environmental impact. Additionally, the EIQ's method of combining a large amount of quantitative data into a single qualitative value can result in the loss of valuable information. This approach can obscure the nuances of pesticide application, such as the cumulative impacts of repeated application over time. Furthermore, the EIQ framework has been criticized for not adequately incorporating exposure into its calculations. The tool includes components meant to serve as proxies for exposure, such as plant surface half-life, runoff potential, and leaching potential, but these do not accurately estimate the potential exposure (Dushoff et al. 1994; Kniss and Coburn 2015; Peterson and Schleier 2014).

Despite these limitations, our methodology, informed by Kovach et al. (1992), aims to provide a fair and accurate comparison of the EIQ-FU values of different herbicides across the studied periods. However, we emphasize that the EIQ-FU should be interpreted within the context of these acknowledged limitations and as part of a broader integrated pest management strategy.

In selecting herbicides for our study periods, the primary criterion was the frequency of use reported by farmers, specifically the percentage of respondents indicating the application of these herbicides during the in-crop phase. The most frequently reported herbicides were cross-referenced with scientific data on the most used or sold herbicides in Saskatchewan or, if Saskatchewan data were unavailable, neighboring provinces. This two-step verification process led to the selection of MCPA, 2,4-D (ethyl ester), diclofop-methyl, trifluralin, and bromoxynil for 1991 to 1994 and glyphosate, glufosinate, imazamox, 2,4-D, and clethodim for 2016 to 2019.

Additionally, for the period 2016 to 2019, our herbicide selection was guided by the prevalent agricultural practices in Saskatchewan and Alberta, substantiated by empirical sales data and weed control strategies. Notably, glyphosate, glufosinate, and 2,4-D were among the top-selling AIs in Alberta in 2018, as indicated by the Alberta pesticides sales report (Environment and Parks 2020). This report highlights the widespread use of these herbicides in regional agriculture, justifying their inclusion in our analysis for this period.

Furthermore, the relevance of imazamox in this time frame is underscored by its documented efficacy in controlling broadleaf and grassy weeds, particularly in pea (*Cicer* spp., *Lathyrus* spp.) and soybean [*Glycine max* (L.) Merr.] crops. It is claimed that imazamox's tank mixability, residual control, and flexible recropping options have made it a preferred herbicide in western Canadian agriculture (ADAMA West Canada 2021). This aligns with our research's focus on herbicides with significant agricultural impact in the region. The reevaluation of imazamox by Health Canada's Pest Management Regulatory Agency further solidifies its significance. The reevaluation, which assesses the risks and benefits of pesticides to ensure compliance with modern health and environmental standards, confirms the continued relevance of imazamox in contemporary agricultural practices (PMRA 2017). Similarly, herbicide selection for 1991 to 1994 was also based on their extensive use in Saskatchewan. This assertion is supported by environmental studies in the region, such as research by Waite et al. (2004), which reported on the environmental concentrations of these herbicides near Regina, Saskatchewan. The study's findings demonstrate the significant presence of these herbicides in various environmental media, indicating their widespread application and potential environmental impact.

In evaluating the changes in herbicide use and their impact on the EIQ of farming systems, we acknowledge the increased diversity in herbicide use in the later period (2016 to 2019) compared to the earlier period (1991 to 1994). This diversity reflects evolving agricultural practices and is an important factor in our analysis. However, our primary objective is to assess overall trends and environmental impacts of herbicide use, rather than focusing on acreage-specific comparisons. This approach allows us to provide broader insights into the dynamic nature of herbicide application and its environmental implications in Saskatchewan.

The first step in determining the EIQ-FU for each herbicide involved identifying the EIQ value for each individual AI. This value, which remains constant, was derived from a comprehensive assessment that includes factors such as the pesticide's inherent toxicity, its potential for runoff, and its impact on nontarget organisms. The EIQ values are sourced from the EIQ database provided by Cornell University (2023).

In the second step of this analysis, we used the application rates for each commercial herbicide product as reported by farmers, measured in liters per acre. If these application rates significantly deviated from the label-recommended rate or were not specified, we utilized the highest recommended rate for the seeded crop as a standard reference. For glyphosate, we adopted a commonly reported rate of 1 L $acre^{-1}$ for the 540 g ae formulation.

In the third step, we utilized the Cornell University EIQ calculator to determine the EIQ-FU for each herbicide, using the application rates reported by farmers and concentrations of AIs from the list of herbicides identified for both the 1991 to 1994 and 2016 to 2019 periods. The EIQ-FU values, generated by the calculator, provide an overview of the environmental impact per unit area. It must be noted that the EIQ-FU value reported in our results, while related to EIQ, is a distinct measure. This value extends the EIQ by considering the actual field use conditions of the pesticides and factoring in the application rates, which can vary over time and between different herbicide formulations. As a result of these differences in application rates and concentrations of the AI in herbicide formulations across the two periods, the EIQ-FU values for the same AI, such as 2,4-D, may vary over time. The field use EIQ calculator provides unitless relative safety ratings, standardized to pounds per acre, based on product weight and application area provided by user.

The research utilizes primary data generated from the Crop Rotation Survey, which was developed and administered online to Saskatchewan crop farmers. Farmers were asked to report on a single field throughout the survey and, if possible, to report on the same field for both the 1991 to 1994 and 2016 to 2019 time periods. The questions were open, closed, and partially open, with space provided for farmers to include additional information to clarify their answers.

The Crop Rotation Survey is divided into four components: seeding and harvest, tillage, fertilizer use, and chemical use. For the purpose of this study, we use the survey section that focused on chemical use, which asked respondents to record the timing, application rates, equipment used, and chemicals applied for all chemical applications. The survey asked farmers to report the product names of the chemicals they used, such as Roundup® Ultra 2 (Bayer Crop Science, St. Louis, MO, USA), instead of the chemical name, such as glyphosate, as well as the rate at which they applied the chemical either in kg/acre or in l/acre. Acres were used as farmers' fields have been surveyed using imperial measurements, such that a section of land is 1 mi^2, or 640 acres.

The initial data set for the 1991 to 1994 period consisted only of respondents who reported to have farmed for this crop rotation period ($n = 75$), and similarly, the 2016 to 2019 data set consisted of people who farmed during that period ($n = 107$). However, the number of respondents who reported to have applied in-crop herbicides varied from one year to another and from one crop rotation to another. A third subset is formed when narrowing the analysis to only those respondents who reported having used chemical products that contain the AIs selected for this analysis. Estimates of EIQs and application rates for the five main herbicides for each crop rotation period are drawn from this last subset and are limited to in-crop herbicide timing. These calculations represent an average of each calculated EIQ-FU and its components, taken over the number of respondents who reported having applied each individual product that contains the selected herbicide for analysis.

In terms of geographical distribution, respondents hailed from all nine provincial regions of Saskatchewan, with a pronounced concentration in the northwest region. Figure 1 is a map of Saskatchewan indicating where the survey participants were located, grouped by rural municipality. The colors on the map indicate how many participants were located in each rural municipality, as shown in the map legend. Although our study's respondent concentration could imply regional bias, this does not significantly undermine the generalizability of our findings. The overall trends in herbicide use and environmental impacts, as analyzed, align with broader agricultural practices across Saskatchewan. It is unlikely that herbicide use patterns differ dramatically across regions to a degree that would substantially skew our results as crop production and rotations are similar throughout the province. However, we suggest that future research could further explore regional variations to enhance understanding.

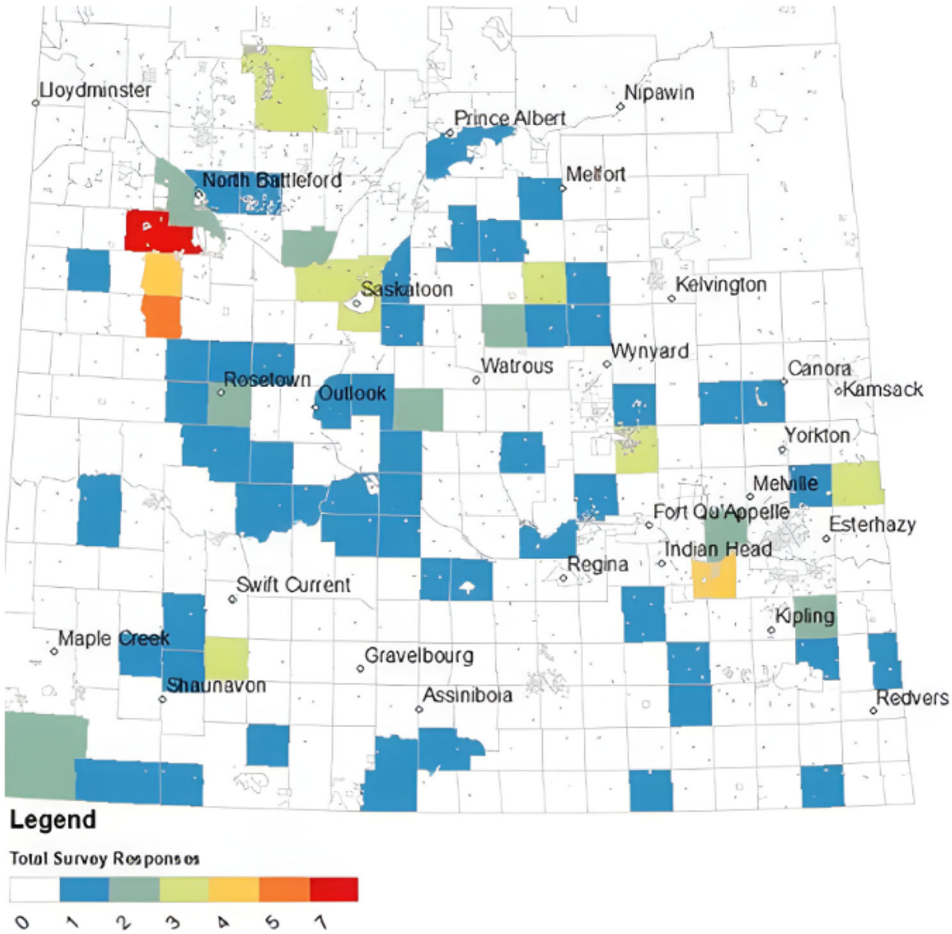

Figure 1. Map of provincial survey participant locations.

When benchmarked against the 2016 Canadian Census of Agriculture, our sample's demographics generally aligned, though with a younger age and a higher educational attainment. This alignment suggests that our sample, despite its unique characteristics, remains representative of the broader Saskatchewan farming community. The data's granularity and the comprehensive nature of the survey ensure that our findings are both robust and policy relevant, providing valuable insights into the evolving agricultural practices in Saskatchewan. Table 1 provides more detailed information on the full survey sample.

Results and Discussion

The data from the two distinct crop rotation periods reveal significant trends in herbicide use in Saskatchewan. In the 1991 to 1994 period, the top five herbicides by use were MCPA, 2,4-D, diclofop-methyl, bromoxynil, and trifluralin, each with distinct environmental impacts based on use patterns and intrinsic properties. Table 2 provides baseline data on the EIQ quotients of each herbicide and shows the grams of AI per acre and the percentage of seedable acres applied. Diclofop-methyl has the highest EIQ-FU at 16.9, closely followed by MCPA at 15.6, while bromoxynil had the lowest at 6.1. Concerning the environmental impact on farmers and farmworkers (EIQ_f), trifluralin, MCPA, and diclofop-methyl exhibited similar values, with diclofop-methyl slightly higher at 11.2. The impacts on consumers (EIQ_c) are lowest, assessing herbicide residues in food and watershed. Notably, MCPA's higher solubility and lower soil adsorption, as discussed by Hiller et al. (2008), indicate its greater potential for leaching and aquatic ecosystem impact compared to 2,4-D, which exhibits different degradation rates and mobility. These properties, combined with the application rate per acre, influence the ecological impact of these herbicides in Saskatchewan's specific environmental and agricultural conditions. Bromoxynil had the least ecological impact (EIQ_e) at 12.1.

Table 3 extends the analysis from Table 2, providing deeper insight into the overall and per acre environmental impact of the herbicides. It highlights the cumulative effect of these herbicides, with a significant emphasis on their ecological impact, constituting 66% of the total EIQ-FU, followed by the impact on farmers and farmworkers (25%) and, lastly, on consumers (9%). Trifluralin shows the highest EIQ-FU per acre, constituting 37% of the total impact, emphasizing its substantial ecological footprint. Conversely, bromoxynil, despite its wide use, had the least impact at 5%. The rates of the top three chemicals applied, trifluralin (37%), MCPA (24%), and diclofop-methyl (23%), reflect evolving patterns in herbicide application.

The top five herbicides for the 2016 to 2019 period were glyphosate, glufosinate, imazamox, 2,4-D, and clethodim. Glufosinate had the highest combined EIQ-FU at 11.6, followed closely by glyphosate at 10.5. Clethodim and imazamox had significantly lower EIQ-FU values at 1.2 and 0.9, respectively.

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Table 1. Total participant demographics compared to Saskatchewan 2016 Census of Agriculture.

	Crop Rotation Survey	2016 Census of Agriculture
	%	
Age (yr)		
<35	25	10
35–54	44	34
≥55	31	56
Education		
Postsecondary education	64	48
High school diploma	31	35
No high school diploma	3	17
Prefer not to say	2	—
Collect off-farm income		
Yes	40	42
No	60	58
Farm size (acres)		
≤399	5	30
400–759	10	15
760–1,119	8	10
1,120–1,599	9	10
1,600–2,239	12	10
2,240–2,879	13	7
2,880–3,519	5	5
≥3,520	37	13
Prefer not to say	1	—

Table 4 provides detailed information on the comparative EIQs of the top in-crop herbicides used between 2016 and 2019.

In the 2016 to 2019 period, ecological impacts dominate the environmental impact, slightly more so than in the 1991 to 1994 period, as presented in Table 5. These impacts account for 73% of the total EIQ-FU, with glyphosate contributing 41% and glufosinate 34% to the total. Our results highlight the significant environmental footprint of these herbicides during this period.

Comparing the environmental impacts of the top five herbicides across the two periods, as shown in Table 6, indicates a general decrease in the EIQ-FU per acre by 65%. This includes a 74% reduction in impact on farmers and farmworkers, a 68% decrease in the impact on consumers, and a 63% decrease in ecological impact. This trend suggests a general reduction in the potential adverse effects of herbicides on the environment, biodiversity, and individuals. Additionally, there is a 45% reduction in the number of grams of AI applied per acre, which reflects a change in herbicide use patterns rather than a direct measure of efficiency.

Statistical analysis confirms strong correlations between the different EIQ components for both periods. In the 1991 to 1994 period, the correlations were $r = 0.983$ ($EIQ_f - EIQ_c$), $r = 0.951$ ($EIQ_f - EIQ_e$), and $r = 0.977$ ($EIQ_c - EIQ_e$). For the 2016 to 2019 period, these values were $r = 0.976$, $r = 0.960$, and $r = 0.875$, respectively. These strong positive correlations for both periods suggest that enhancements in one aspect of environmental impact are closely associated with improvements in others. The paired *t*-test, with a P-value of 0.0652, indicates that while there are notable decreases in EIQ values between the two periods, the differences are not statistically significant at the conventional 5% level. This means that, statistically, we cannot be confident that the differences observed are not due to random choice. Thus, although the trends are promising, they are not statistically conclusive, underlining the need for continued research.

The results provide a view on the evolution of herbicide use and the resulting environmental impacts prior to the commercialization of GM crops compared to recent crop production and herbicide use. Initially, herbicides like MCPA and diclofop-methyl were predominant, but by 2016 to 2019, there was a noticeable shift toward substances like glyphosate and glufosinate, known for their lower environmental impact (Dennis et al. 2018; Duke 2020). This transition aligns with the broader adoption of GM crops and the consequent reduction in tillage for weed control (Brookes 2022; Sutherland et al. 2021). Despite an increase in the number of acres sprayed, the environmental impact of herbicides has decreased, underlining the role of GM crops and technological advancements in introducing less toxic herbicides (Bonny 2016). This shift has been crucial in replacing older, more harmful soil-incorporated and residual herbicides with more benign alternatives (Gunstone et al. 2021).

Smyth et al. (2011) reported a 53% decrease in in-crop herbicide EIQ following a decade of GM crop commercialization. The results from this research contradict predictions that the environmental benefits of GM crops would be fleeting, as our data extend the benefits to 20 yr, showing not only consistent but increased benefits.

The shift away from tillage to herbicide use aligns with the reduced environmental impacts observed over the past 30 yr. Studies have shown the negative effects of tillage on soil quality and greenhouse gas emissions (Awada et al. 2014; Aziz et al. 2013; McConkey et al. 2003; Nath and Lal 2017; Sutherland et al. 2021; West and Post 2002). The preference for herbicides in no-tillage systems represents a more sustainable weed management approach. However, it is important to clarify that our analysis is confined to the use of in-crop herbicides. This is a critical distinction, as conservation tillage impacts primarily the use of preseed herbicides, not in-crop ones. Our study's insights should not be interpreted as covering the broad spectrum of herbicide use influenced by conservation tillage practices.

The trend of restricting modern herbicides like glyphosate presents challenges. Such restrictions could revert farmers to older, more toxic chemicals and increased tillage, countering sustainability efforts. Sustainable management is crucial for long-term environmental and economic health, and farmers are motivated to reduce their operations' environmental impacts. The shift to no-till management since the 1990s indicates a preference for chemical use within these systems as a sustainable weed management strategy (AAFC 2014; Haak 2005; Sutherland et al. 2021).

Continued sustainability requires proper crop rotation and avoiding an overreliance on a single herbicide mode of action to prevent the development of herbicide resistance in weeds. Ongoing research for new herbicides with reduced ecological impacts is crucial. This research's findings on EIQ changes are beneficial to agricultural and environmental policy, underscoring the need for robust evidence in policy debates about herbicide use and the importance of ongoing herbicide development.

Practical Implications

These results underscore the significant evolution in herbicide use and its environmental impacts in Saskatchewan agriculture, particularly highlighting the transition from tillage to herbicide-resistant cropping systems. This shift, predominantly toward less environmentally impactful herbicides like glyphosate and glufosinate, illustrates a strategic adaptation by farmers to enhance sustainability. Our analysis, grounded in comprehensive EIQ data across different crop rotation periods, demonstrates a notable reduction in the environmental and toxicological impacts of herbicides used. This affirms the role of technological advancements in agriculture, such as the development of more environmentally and

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Table 2. Baseline EIQs for in-crop herbicides applied in Saskatchewan (1991 to 1994): analysis of active ingredient use, EIQ factors, and ecological impacts.[a]

Herbicide	EIQ_f	EIQ_c	EIQ_e	EIQ-FU	Rate	Seedable acres[b]
					g ai acre^{-1}	%
MCPA	10.8	3.7	32.4	15.6	330	25
2,4-D	8.8	2.6	13.3	8.3	280	19
Bromoxynil	4.2	2.1	12.1	6.1	168	15
Diclofop-methyl	11.2	4.6	35.0	16.9	291	9
Trifluralin	10.8	3.9	28.0	14.5	563	5

[a]Abbreviations: ai, active ingredient; EIQ, environmental impact quotient; EIQ_c, EIQ on consumers; EIQ_e, EIQ on the ecology; EIQ_f, EIQ on farmers and farmworkers; EIQ-FU, field use EIQ.
[b]Proportion of area to which each herbicide was applied. The annual percentages were summed for the 1991 to 1994 period.

Table 3. Detailed environmental impact assessment of in-crop herbicides in Saskatchewan (1991 to 1994): cumulative and per acre impacts on ecology, farmers, and consumers.[a]

	EIQ_f	EIQ_c	EIQ_e	EIQ-FU	Herbicide contribution to total impact[b]
	acre^{-1}				%
Herbicide					
MCPA	3,564	1,221	10,692	5,148	24
2,4-D	2,464	728	3,724	2,324	11
Bromoxynil	706	353	2,033	1,025	5
Diclofop-methyl	3,259	1,339	10,185	4,918	23
Trifluralin	6,080	2,196	15,764	8,164	37
Cumulative effect[c]	16,073	5,837	42,398	21,579	
Percentage category-wise distribution of total impact[d]	25	9	66		100

[a]Abbreviations: EIQ, environmental impact quotient; EIQ_c, EIQ on consumers, reflecting the potential impact of herbicide residues on consumers; EIQ_e, EIQ on the ecology, indicating effects on biodiversity and environmental health; EIQ_f, EIQ on farmers and farmworkers, quantifying occupational exposure; EIQ-FU, field use EIQ.
[b]Proportion of the total ecological, farmworker, and consumer impacts attributed to each individual herbicide. It helps in understanding the relative significance of each herbicide within each impact category.
[c]Encompasses the total environmental impact of all herbicides combined, across all impact categories, over the 1991 to 1994 period. This indicator is essential for assessing the overall ecological footprint of herbicide use.
[d]Proportion of the total environmental impact attributable to each impact category (ecological, farmworker, and consumer) for all herbicides combined. The percentages in this row indicate the overall distribution of total environmental impact across these three categories.

Table 4. Comparative EIQs of top in-crop herbicides in Saskatchewan (2016 to 2019): glyphosate, glufosinate, imazamox, 2,4-D, and clethodim.[a]

Herbicide	EIQ_f	EIQ_c	EIQ_e	EIQ-FU	Rate	Proportion of seedable acres[b]
					g ai acre^{-1}	%
Glufosinate	6.9	3.5	20.3	11.6	248	13
Glyphosate	5.5	2.1	23.9	10.5	324	12
Clethodim	0.8	0.5	2.1	1.2	49	11
Imazamox	0.5	0.4	2.0	0.9	158	11
2,4-D	3.3	1.3	14.4	6.3	297	8

[a]Abbreviations: ai, active ingredient; EIQ, environmental impact quotient; EIQ_c, EIQ on consumers; EIQ_e, EIQ on the ecology; EIQ_f, EIQ on farmers and farmworkers; EIQ-FU, field use EIQ.
[b]Proportion of area to which each herbicide was applied. The annual percentages were summed for the 2016 to 2019 period.

Table 5. Comprehensive environmental impact assessment of in-crop herbicides in Saskatchewan (2016 to 2019): ecological, farmer, and consumer effects.[a]

Herbicide	EIQ_f	EIQ_c	EIQ_e	EIQ-FU	Herbicide contribution to total impact[b]
	acre^{-1}				%
Glufosinate	1,711	868	5,034	2,877	34
Glyphosate	1,782	680	7,744	3,402	41
Clethodim	39	25	103	59	1
Imazamox	79	63	316	142	2
2,4-D	980	386	4,277	1,871	22
Cumulative effect[c]	4,592	2,022	17,474	8,351	
Percentage category-wise distribution of total impact[d]	19	8	73		100

[a]Abbreviations: EIQ, environmental impact quotient; EIQ_c, EIQ on consumers; EIQ_e, EIQ on the ecology; EIQ_f, EIQ on farmers and farmworkers; EIQ-FU, field use EIQ.
[b]Proportion of the total ecological, farmworker, and consumer impacts attributed to each individual herbicide. It helps in understanding the relative significance of each herbicide within each impact category.
[c]Encompasses the total environmental impact of all herbicides combined, across all impact categories, over the 1991 to 1994 period. This indicator is essential for assessing the overall ecological footprint of herbicide use.
[d]Proportion of the total environmental impact attributable to each impact category (ecological, farmworker, and consumer) for all herbicides combined. The percentages in this row indicate the overall distribution of total environmental impact across these three categories.

Table 6. Environmental impact trends of top five in-crop herbicides from 1991 to 1994 and from 2016 to 2019: reductions in EIQ-FU and effects on farmers, consumers, and ecology.[a]

Comparison	1991–1994	2016–2019	Change
	acre^{-1}		%
EIQ-FU	2,733	954	−65
EIQ_f	2,062	528	−74
EIQ_c	727	235	−68
EIQ_e	5,390	1,972	−63
g ai	215	118	−45

[a]Abbreviations: ai, active ingredient; EIQ, environmental impact quotient; EIQ_c, EIQ on consumers; EIQ_e, EIQ on the ecology; EIQ_f, EIQ on farmers and farmworkers; EIQ-FU, field use EIQ.

biodiversity-friendly herbicide formulations and the adoption of precision agriculture techniques.

For practitioners, these insights emphasize the need to adopt herbicide-resistant crops as a sustainable approach to weed management, potentially offering environmental benefits. This is especially relevant in the context of increasing global concerns about environmental sustainability and the need for more efficient farming practices. Additionally, the study highlights the importance of balancing chemical use with environmental stewardship, suggesting a continued need for innovation in agricultural practices. This balance is key to ensuring long-term soil health and ecosystem stability, which are essential for sustainable agriculture.

For those in the field, this research provides a valuable perspective on the long-term trends in herbicide use, offering a framework to make informed decisions that align with agricultural practices. The shift toward using herbicides with a lower EIQ, as demonstrated in our findings, reflects an ongoing effort to minimize the environmental footprint of crop production. It is important for practitioners to stay informed about these evolving trends and to integrate such insights into their weed management strategies to maintain both crop productivity and environmental integrity.

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