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Correlating Genetically Modified Crops, Glyphosate Use and Increased Carbon Sequestration

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Abstract: In the early 1990s, tillage was the leading form of weed control, with minimum/zero-tillage management practices incapable of long-term continuation. Presently, weed control through tillage has virtually disappeared as cropland management systems have transitioned largely to continuous cropping, with zero to minimal soil disturbance. Research was undertaken to examine what was driving this land management transition. A carbon accounting framework incorporating coefficients derived from the Century Model was used to estimate carbon sequestration in the Canadian province of Saskatchewan. The results quantify the transition from farmland being a net carbon emitter to being a net carbon sequesterer over the past 30 years. This evidence confirms the correlation between genetically modified, herbicide-tolerant crops and glyphosate use is a driver of the increased soil carbon sequestration. The removal of tillage and adoption of minimal soil disturbances has reduced the amount of carbon released from tillage and increased the sequestration of carbon through continuous crop production. Countries that ban genetically modified crops and are enacting legislation restricting glyphosate use are implementing policies that Canadian farm evidence indicates will not contribute to increasing agricultural sustainability.

Keywords: carbon dioxide; climate change; herbicide tolerance; land management change; Saskatchewan; soil organic carbon; sustainability

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1. Introduction

In the late 1980s and early 1990s, Canadian farmers began shifting away from traditional land management practices, such as fallowing land for a full year and using tillage to control weeds, towards more sustainable practices. Historically, the preferred weed control option was to fallow a field and till it frequently throughout the growing season to ensure continuous weed growths were eradicated, a practice known as summerfallow. These changes have had positive impacts on the environmental footprint of crop production, including decreasing greenhouse gas (GHG) emissions through reduced fossil fuel consumption and soil disturbance [1], and have improved soil quality [2]. One benefit contributed by these adoptions is improved carbon (C) sequestration in agricultural soils [3,4].

Carbon sequestration plays an important role in reducing net GHG emissions. Greenhouse gas emissions are offset by transferring carbon dioxide (CO_2) from the atmosphere into soil storage pools through photosynthesis, becoming soil organic carbon (SOC). Previous research suggested the capacity of these soil storage pools would be reached 15–20 years after the adoption of sustainable management practices [4,5], eliminating future sequestration benefits. However, recent research indicates that through continuous utilization of sustainable practices, soil storage potential can be increased beyond 20–30 years after land management changes are adopted [2,6].

There is a complementary relationship between the adoption of herbicide-tolerant (HT) canola and conservation tillage, resulting in corresponding changes in GHG emissions. One study found that after ten years of HT canola production on the Canadian prairies, no-tillage (NT) land management had grown to over 3.3 million hectares, resulting in 436,000 Mg of annual C sequestration relative to conventional tillage (CT) production [7]. Shrestha et al. [8] conducted a GHG inventory analysis of 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. [9] 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. A study of emission changes after 22 years of Canadian HT canola production concluded that the resulting C sequestration was 2.51 billion kg of CO_2 between 1996–2018 [1].

Changes in equipment size, reductions in the cost of glyphosate, improvements in crop input technologies, and crop genetics have all positively contributed to reducing tillage practices [10,11]; nonetheless, mounting evidence suggests that sustained land-use changes would not be possible without genetically modified (GM) HT crops, which were commercialized in 1995 [12–15]. The use of tillage was marginally decreasing in Western Canada prior to the commercialization of GMHT crops in 1995; however, the long-term challenge of controlling weeds effectively without damaging crops placed limitations on reductions in the use of tillage and summerfallow [16–18]. Environmental benefits from GMHT crops include a reduction in fossil fuel consumption [1,7] and a reliance on more environmentally benign chemicals, such as glyphosate [1,17,19]. One significant contribution provided by GMHT crops is the opportunity for farmers to reduce their tillage and summerfallow practices, contributing to improved carbon sequestration due to the efficient weed control provided by the technology [1,10,20,21].

Though farmers' adoption of sustainable land management practices has contributed to improving agricultural carbon sequestration, the challenge is that these contributions are not often included in environmental or climate change mitigation policy discussions. Furthermore, the attribution of various technologies, such as GMHT crops and glyphosate, to these sustainable adoptions are often unrecognized, and in some cases, are outweighed by discussions of the hypothetical and speculative risks surrounding these technologies. This article presents the initial results from a multi-year, Canadian prairie-wide farm survey by examining the relationship between GMHT crop adoption, glyphosate use, and the changes in soil carbon sequestration resulting from changes in Saskatchewan crop farmers' land management practices over the past 30 years.

2. Methods

2.1. Survey Methodology

Data for this article was collected through an online survey of Saskatchewan crop farmers between November 2020 and April 2021. Participants were recruited through a social media campaign, newspaper articles, radio advertisements, and word of mouth spread by family and friends. Information about the survey was also shared by provincial commodity commissions, the Saskatchewan Ministry of Agriculture, and various industry groups. The survey took participants between three to five hours to complete, and each participant was incentivized with payment of up to $200 upon survey completion. Survey participants answered questions regarding their land management practices during two time periods, 1991–1994 and 2016–2019, to determine how their practices changed over the past 25 years. The University of Saskatchewan requires all surveys to be reviewed and approved by an ethics committee. However, if human subjects are not the direct focus of an intended survey and the survey objective is to gather non-human data, researchers can apply for an exemption from ethics approval. This survey was granted an official exemption from ethics approval by the University of Saskatchewan's Research Ethics Board.

The survey included four components, in which participants were compensated $50 for the completion of each; thus, if participants completed all four sections, they were compensated $200. The first section followed the seed from planting to harvest, examining the practices, equipment, and inputs used for seedbed preparation, planting, in-crop field maintenance, and harvest. The second section documented application rates, methods, and timings of fertilizer use. The third section examined tillage and summerfallow practices by documenting the number of tillage applications, tillage depth, and implements employed. The final survey section focused on chemical use and asked respondents to record the timing, application rates, equipment used, and chemicals applied for all chemical applications. Demographical questions, including field location, farmer age, farmer education level, farm size, and whether the farmer also collected off-farm income, ensured participants were eligible to participate in the survey and allowed for comparison of the sample demographics to the demographics of the population of Saskatchewan farmers.

An additional questionnaire at the end of the survey addressed the important question of attribution. Questions in this section asked farmers to comment on to what extent they believed the adoption of HT crops, GM crops, and glyphosate facilitated the adoption of conservation tillage and reduced summerfallow. First, participants were asked to assign a factor from one to ten for each of the three technologies, representing its level of attribution to their reductions in tillage and summerfallow practices. A factor of one meant the technology did not at all facilitate the adoption and a factor of ten meant the technology played a major role. Next, participants were asked to estimate what percentage of their land would include summerfallow management in the absence of HT crops. Finally, participants had the opportunity to comment on what would be different about their operation today without the use of HT crops, other GM crops, and glyphosate.

Farmers were asked to choose one single field to report on throughout the survey, and if possible, to report on the same field for both the 1991–1994 and 2016–2019 time periods. The questions were open, closed, and partially-open, and space was provided for farmers to include more information, if necessary, to clarify their answers. The same questions were asked for both periods in all survey components, allowing for a direct comparison of participant responses between the time periods.

The survey collected extensive details of farmers' operations, providing the opportunity for an investigation into many aspects of on-farm sustainability changes. This analysis focused on changes in SOC levels, and therefore only responses to questions that helped to address this research question were relevant. The location of a farmer's field was used to segment the responses into regions and the seedable hectares of the field were used to quantify the relative impact of the change in farm management practices per ha. The crops planted and their yield were used to calculate the harvest index (HI), an important factor for determining crop residue levels. In addition, the residue management practices identified determined whether the crop residues have a positive effect on soil C sequestration. The reported frequency and timing of tillage applications, as well as the tillage implements used, helped to classify tillage practices as NT, MT, or CT. Finally, the reported frequency of summerfallow within a four-year rotation was important for the identification of those farmers, in both time periods, who have removed summerfallow from their crop rotations.

2.2. Carbon Accounting Framework

Quantification of GHG emissions and carbon sequestration is often accomplished through C accounting frameworks. Accounting models quantify GHG emissions and removal (sequestration) by a combination of modeling techniques and empirical data. Similar to financial accounting, emission reductions count as "credits", while increases count as "debits" [22]. One specific C accounting framework developed to estimate agricultural energy input, output, and efficiency for quantification purposes is the Prairie Crop Energy Model (PCEM) [23]. The accounting framework used in this article has been adapted from the PCEM model used by Awada and Nagy [24] in their assessment of GHG sources and sinks in Alberta and Manitoba and by Smyth and Awada [25] in their assessment of Saskatchewan GHG sources and sinks. In their study, each cropping activity within each year and crop district was assigned a coefficient representing its environmental impacts. The coefficients were adapted from empirical studies of SOC changes on the Canadian prairies and adjusted based on the crop type, residue levels, and yield. In this article, the cropping activities used in the accounting model focus on changes in tillage and summerfallow practices.

Soil C coefficients are an important element in the quantification of net agricultural emissions. Although soil sampling techniques are the most accurate measurement of changes in SOC levels, often it is not possible to physically measure SOC changes, especially over long time periods. Carbon coefficients estimate how SOC levels change in response to a change in land management practice. Numerous empirical studies of the impacts of conservation tillage adoption and the elimination of summerfallow have estimated C coefficient values. West and Post [4] conducted an extensive survey of the empirical literature and found an average increase of 0.57 ± 0.14 Mg C/ha/yr from conservation tillage adoption. McConkey et al. [26] found annual SOC increases between 0.067–0.512 Mg/ha/yr from the adoption of NT and 0.027–0.430 Mg/ha/yr from the shift to continuous cropping across Saskatchewan. Grant et al. [27] found net emission reductions of 0.61 Mg CO_2 equivalents/ha/yr in Canada from converting to NT, and reductions of 0.56 Mg CO_2 equivalents/ha/yr from the elimination of summerfallow. Liebig et al. [3] concluded that NT adoption in the Northwestern United States and Canada resulted in SOC increases of 0.27 ± 0.19 Mg/ha/yr. Gan et al. [28] found that continuous wheat production gained 1.34 Mg CO_2 equivalents/ha/yr, on the Canadian prairies, almost double that of rotations containing fallow. Sperow [29] used the 2006 Intergovernmental Panel on Climate Change (IPCC) factors to estimate SOC changes from changes in cropping activities and found SOC increases of 0.16–0.24 Mg/ha/yr from summerfallow reductions across the United States.

The C coefficients used in this analysis were developed using the Century Model for Canada's national GHG inventory reporting [30] and align well with the estimates from existing literature discussed above (Table 1).

Table 1. Carbon Change Factors (Mg/ha/yr).

	Semiarid Prairie	Subhumid Prairie
No tillage (NT)	0.1	0.15
Minimum tillage (MT)	0.04	0.07
Conventional tillage (CT)	−0.1	−0.15
Removal of summerfallow	0.3	0.3
Inclusion of summerfallow	−0.3	−0.3

These factors were chosen because they are targeted to the cool Canadian climate under study, they fall within confidence limits of the estimates calculated using IPCC's tier 1 methodology and those within the existing empirical literature based on a comparison conducted by VandenBygaart et al. [31], and they provide conservative estimates for the sequestered C. Negative coefficients represent emissions from CT and summerfallow practices, respectively. The higher sequestration in the subhumid prairies is related to the higher soil productivity in this region, largely due to higher soil moisture conditions [31].

Environmental gains from conservation tillage adoption are not necessarily permanent. Factors such as moisture and climate conditions, pest infestations, and crop residue levels may constrain a farmer's ability to maintain a long-term NT system [32]. However, the negative effects of infrequent tillage within a long-term conservation tillage system are not likely to adversely affect SOC content and soil quality [33]. Although C is released from soil during tillage, as the duration between tillage events increases, the resulting SOC losses decrease. Within a long-term NT system, SOC losses from a single tillage event can be as low as 1% [34]. The coefficient values discussed above were developed assuming constant management practices, as would be the case in small-plot studies where each plot of soil is assigned a consistent treatment for the duration of the study. However, deviations from farmers' typical management practices are common for reasons such as atypical weather conditions, necessary residue management, or weed infestations. The application of these C coefficients to farm-level data must take into consideration slight deviations in farmers' management practices. Therefore, coefficients for tillage practices are applied based on the practices used each year.

The coefficients representing the inclusion or elimination of summerfallow practices are not assessed on a year-by-year basis. Instead, they represent long-term increases or reductions in summerfallow areas. Therefore, they are used to determine differences in SOC gains between rotations containing summerfallow and rotations in which summerfallow has been eliminated. For this reason, the coefficient for the removal of summerfallow was only applied to hectares to which summerfallow management had been eliminated.

In this analysis, the coefficients were adjusted to account for changed residue levels. This adjustment was based on the crop yield and HI. The HI is the ratio of the harvested grain to the total above-ground matter of the plant shoot [35] and is affected by environmental conditions, plant stresses, and cultivar selection [36]. The HI is commonly used in C accounting systems by calculating the difference between the C in the plant shoot and the grain. This index varied significantly among crop types and is largely determined by how efficiently a crop produces grain from the plant matter. Therefore, crops with a higher HI have lower crop residue levels, resulting in lower levels of C returned to the soil through post-harvest residues [37]. In addition, though previous research has suggested that initial SOC levels affect future sequestration potential due to soil saturation, uncertainty regarding the variability in saturation points exists, as observations exist both of soils with high SOC levels gaining further SOC and soils with low SOC losing SOC. Sufficient base level, regional estimates of SOC across Saskatchewan are not available. Therefore, in this analysis, all soils are assumed to have equal sequestration potential.

The classification of tillage systems based on management practices varies within the literature. However, based on the tillage classification systems defined in previous literature [7,31,38], for this research CT is classified as one or more annual cultivation passes in the semiarid prairies and more than one in the subhumid prairies, MT in the subhumid prairies is classified as one cultivation pass, harrowing is an MT operation in both regions, and NT in both regions includes no tillage or harrowing applications.

Currently, the extent of the interactive effects between SOC gains from a change in tillage practices and the removal of summerfallow has not been confirmed in the literature [26]. It is estimated that the two practices together would sequester more C than either individual practice, but would likely not sequester their sum, as the two practices are typically complementary [39]. Therefore, in the present analysis, the SOC gains from changes in tillage practices and changes in summerfallow are calculated using Equations (1) and (2) and presented separately. Only practices that contribute positively to SOC levels, including NT, MT, and the elimination of summerfallow, are adjusted for crop residue levels. Practices that contribute to net soil emissions, including CT and the inclusion of summerfallow management, are not affected by post-harvest crop residue levels. Therefore, the net effects from these practices are calculated by simply taking the area under the cropping practice and multiplying it by the corresponding carbon coefficient.

Equation (1) Net change in SOC from changes in tillage practices

$$\Delta SOC_{Tt} = \sum_{i=1}^{9} \sum_{j=1}^{3} \left[A_{jti} \times SR_{ji}\right] \times \left[R_{jti} \times RR\right] \times RT_{ti} \tag{1}$$

Equation (2) Net change in SOC from changes in summerfallow practices

$$\Delta SOC_{SFt} = \sum_{i=1}^{9} \sum_{j=1}^{2} \left[A_{jti} \times SR_{ji}\right] \times \left[R_{jti} \times RR\right] \times RT_{ti} \tag{2}$$

ΔSOC_{Tt} = the net change in SOC resulting from a change in tillage practices in each year *(t)*.

ΔSOC_{SFt} = the net change in SOC resulting from the inclusion or removal of summerfallow from crop rotations in each year (t).

$\sum_{i=1}^{9}$ = summation of the effects of cropping practices in each region (i).

$\sum_{j=1}^{3}$ = summation of sequestration effects from the three tillage systems (j).

$\sum_{j=1}^{2}$ = summation of sequestration effects from the inclusion or removal of summerfallow (j).

A_{jti} = area under each cropping practice (j) in each year (t) in each region (i).

SR_{ji} = the sequestration rate of each cropping practice (j) in each region (i).

$R_{jti} = \left(\frac{Y_{jti}}{HI_{jti}}\right) * \left(1 - HI_{jti}\right)$, where $HI_{jti} = \alpha_{ji} + \left(\beta_{ji} * Y_{jti}\right)$ = the residue of cropping practice (j) in each year (t) in each region (i). Y_{jti} is the crop yield (Mg/ha) for each cropping activity (j) in each year (t) in each region (i). HI_{jti} is the HI of the cropping activity (j) in each year (t) in each region (i), calculated by the relationship between yield and HI, where α_{ji} denotes the intercept and β_{ji} denotes the coefficient [40].

RR = 0.3 = rate of C input to the soil from crop residues [25,41].

RT_{ti} = dummy variable for residue removal in each year (t) in each region (i). If residues are removed from the field upon harvest, this variable is assigned a value of 0, indicating that no positive sequestration effects occur. If residues are left in the field, the variable is assigned a value of 1.

3. Results

The survey was completed by 137 Saskatchewan crop farmers. After incomplete and duplicated responses were removed, the final sample size consisted of 127 farmer data sets. Sixty-four participants provided information on land use and crop rotation practices for the 1991–1994 period, and 126 provided identical information for the 2016–2019 period. Sixty-three survey participants provided data for both time periods. T-tests revealed no statistical differences between the land management practices of the sample of participants who farmed during both periods (n = 63) and the total survey sample for both the 1991–1994 time period (n = 64) and the 2016–2019 time period (n = 126) at the 95% confidence level ($p > 0.05$).

Compared to the total population of Saskatchewan grain and oilseed farmers from the 2016 Canadian Census of Agriculture of 21,505 [42], the total survey sample provided a 95% confidence level in the data with a 9% margin of error. The 64 responses from 1991–1994 in comparison to the 1991 Census of Agriculture Saskatchewan farmer population (58,650) [43] provided a 95% confidence level in the surveyed 1991–1994 data with a 12% margin of error. This sample size can be compared to the sample size of 136 commercial farms included in the Prairie Soil Carbon Balance Project, led by the Saskatchewan Soil Conservation Association, between the late 1990s and 2018 [6]. Significant context regarding Saskatchewan soil carbon sequestration has been drawn from the results of this important, long-term study, indicating the sample size of our survey was sufficient to draw analyses and conclusions from.

Table 2 shows the demographics of the survey sample benchmarked against the Saskatchewan proportion of the 2016 Canadian census of agriculture participants [44–47].

Table 2. Participant demographics compared to Saskatchewan 2016 census of agriculture data.

	Crop Rotation Survey	2016 Census of Agriculture
Age		
Under 35	28%	10%
35–54	40%	34%
55+	32%	56%
Education		
Post secondary education	59%	48%
High school diploma	35%	35%
No high school diploma	3%	17%
Prefer not to say	3%	0%
Collect Off-Farm Income		
Yes	41%	42%
No	59%	58%
Farm Size		
Under 399 acres	5%	30%
400–759 acres	9%	15%
760–1119 acres	8%	10%
1120–1599 acres	9%	10%
1600–2239 acres	14%	10%
2240–2879 acres	11%	7%
2880–3519 acres	6%	5%
3520 acres or more	35%	13%
Prefer not to say	2%	–

The survey sample, overall, was younger, had achieved a higher level of education, and operated larger farms than the census of agriculture sample. These variations can, in part, be due to participants who pursued post-secondary education at the University of Saskatchewan themselves being more interested in contributing to academic research from their alma mater. In addition, younger farmers might be more comfortable completing the survey in an online format. Survey respondents were generally farming larger amounts of land than reported in the census data. Previous literature suggested that larger farms may be more likely to adopt innovative technologies, such as NT, to increase efficiencies and cut costs [48,49]. Therefore, operators of larger farms in Saskatchewan, who were early adopters of NT technology, might be more interested in reporting their farm's adoption of sustainable practices than smaller farms whose capacity may have constrained these adoptions initially. However, the overall sample is representative of Saskatchewan farmers and provided a sufficient dataset for analysis.

Survey participants were asked to indicate to what extent the introduction of various technologies contributed to their adoption of NT, minimum tillage (MT), and the removal of summerfallow. The average attribution factors assigned by farmers for HT canola, glyphosate, and other HT crops are presented in Table 3, quantifying farmers' perceptions of how various innovative technologies facilitated their adoption of sustainable land management practices.

Table 3. Attribution of various technologies to sustainable land management practices.

To What Extent Do You Believe Each of These Technologies Facilitated the Adoption of Reduced Tillage and Summerfallow? (1 = Did Not at All Facilitate, 10 = Played a Major Role in Facilitating)			
	HT Canola (n = 116)	**Glyphosate (n = 117)**	**Other HT Crops (n = 109)**
Mean	7.3	9.0	5.2
Standard deviation	2.8	1.95	3.15
Margin of error	0.51	0.36	0.60

Participants reported that glyphosate facilitated the reduction of tillage and summerfallow practices to the greatest extent; however, as a complementary technology, HT crops contributed to these management changes. The mean contribution factor of HT canola to a reduction in tillage and summerfallow was 7.3 out of 10, and for glyphosate, 9.0. The lower attribution factor assigned to other HT crops (5.3 out of 10) in this sample is to be expected, as HT canola is planted on far greater acreage than any other HT crop in Saskatchewan. On average, between 2016–2019, 4.87 million hectares were planted to canola in Saskatchewan, making up about 32% of Saskatchewan's total cropland [50].

Of the total area planted to canola in Canada, HT varieties increased from 97% in 2014 to 100% in 2017, indicating full adoption. A similar trend can be seen for GM corn and soybean varieties in Canada. Adoption of GM corn varieties increased from 95% in 2014 to 100% in 2017, while the adoption of GM soybean varieties has remained relatively stable at 95% between 2014–2017 [50]. Overall, the high adoption rates reveal the importance of GM and HT traits for Canadian grain farmers. Previous farm survey research regarding GMHT canola production revealed that 12–17% of farmers reported they would plant a field to glyphosate-tolerant canola and get such exceptional weed control that they did not need to spray for weeds the following year [7,51]. Some did report they had to make one herbicide application to control volunteer canola, typically using 2,4-D.

Survey participants were also asked what percentage of their land would include summerfallow management in the absence of HT crops. The average response from 104 participants was 23%, with a standard deviation of 26% and a margin of error of 5%. When 23% of the land was compared to the 1% of land currently managed with summerfallow in the survey sample, this increase represents a significant step backwards in Saskatchewan farmers' soil sustainability efforts, should access to glyphosate or HT crops be restricted.

Survey participants were invited to comment on how their operations would change in the absence of various technologies. In the absence of HT crops, the most commonly reported change from 107 respondents was a change in chemical use (30%), followed by a decrease in yield and profitability (28%), change in crop rotation (21%), an increase in tillage (20%), and reversion to summerfallow (11%). Comparatively, the most commonly reported on-farm change in the absence of glyphosate (n = 115) was an increase in tillage (54%), followed by a decrease in yield and profitability (37%), a change in chemical use (23%), and reversion to summerfallow (14%). Four percent of participants reported that they would not be farming without the use of glyphosate. Examples of participant responses can be seen in Box 1.

Using the Prairie Crop Energy Model (PCEM) accounting framework, the changes in SOC levels resulting from changes in management practices were estimated. Survey results show that between 1991–1994 and 2016–2019, the percentage of hectares in the survey sample that included summerfallow management as part of their crop rotation decreased from 44 to 1%. Hectares that included CT management decreased from 51 to 3%, while hectares that included MT and NT management increased from 35 to 42% and 14 to 55%, respectively.

The net change in SOC levels from changes in cropping practices is presented as a net amount per ha. For changes in tillage practices, the net effect per ha was calculated by summing the SOC gains resulting from the adoption of NT and MT practices, subtracting the C emitted from the soil from the use of CT, and dividing this net effect by the total hectares included in the sample (Figure 1).

Similarly, the net SOC gains from changes in summerfallow practices are the difference between the SOC gained from hectares on which summerfallow management has been removed, and the C emitted from the soil from hectares managed with summerfallow, divided by the total hectares included in the survey sample (Figure 2).

The annual net change in SOC from tillage in 1991–1994 was negative, meaning that Saskatchewan soils released more C from tillage practices than was sequestered. However, by 2016–2019, the annual net change in SOC from conservation tillage had increased to

0.12 Mg/ha. Similarly, between 1991–1994, annual net SOC gains from the removal of summerfallow were negligible (0.03 Mg/ha). This is to be expected, as survey results indicate that just over half of hectares (56%) were no longer managed with summerfallow during 1991–1994. By 2016–2019, 0.42 Mg/ha SOC was being stored each year from the virtual elimination of summerfallow.

Box 1. Participant comments on how farm operations would change in the absence of HT crops and glyphosate.

1. Responses to the question: What would change in the absence of HT crops?

"More summer fallow and increased passes of tillage."

"Lower yields. Lower grain quality. The farm would be less profitable therefore I could not utilize the advances in technology."

"There would be challenges maintaining a rotation - if we couldn't control the weeds in those crops we would be reluctant to seed them. Tighter rotations with other crops could lead to more disease issues. Alternatively we could incorporate more summerfallow, likely leading to more soil erosion."

"We would likely struggle to keep a 3 year rotation as both canola and lentils would be poor weed competitors with very limited herbicide options. Yields of these crops would be significantly lower which is hard to image with canola being a significant cash crop on many farms."

"There would be more land with wind and water erosion. There would be a lot less food."

2. Responses to the question: What would change in the absence of glyphosate?

"Everything - we'd be back to summerfallow every 3rd or 4th year."

"Zero till farming would be very difficult or next to impossible. This would have a negative impact on soil quality and crop yields."

"Without glyphosate my need for other more expensive chemicals would go way up. I would have to use more chemical to get less weed control."

"It would severely impact farming practices in Western Canada. More tillage would be needed again and with it more erosion and moisture loss."

"Could not farm the way we do. Glyphosate enables zero tillage and has reduced soil erosion to near zero. It is critical for soil health."

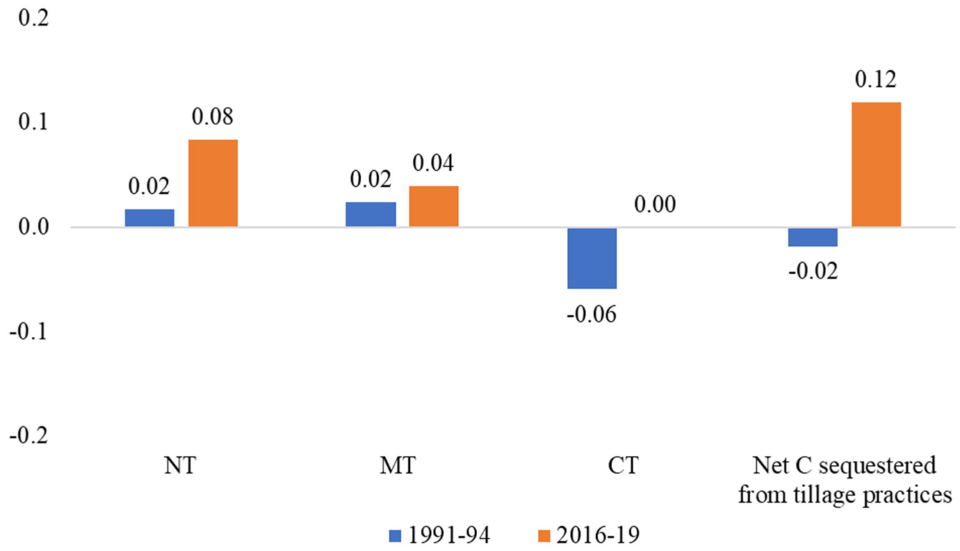

Figure 1. Change in SOC from changes in tillage practices (Mg/ha/year).

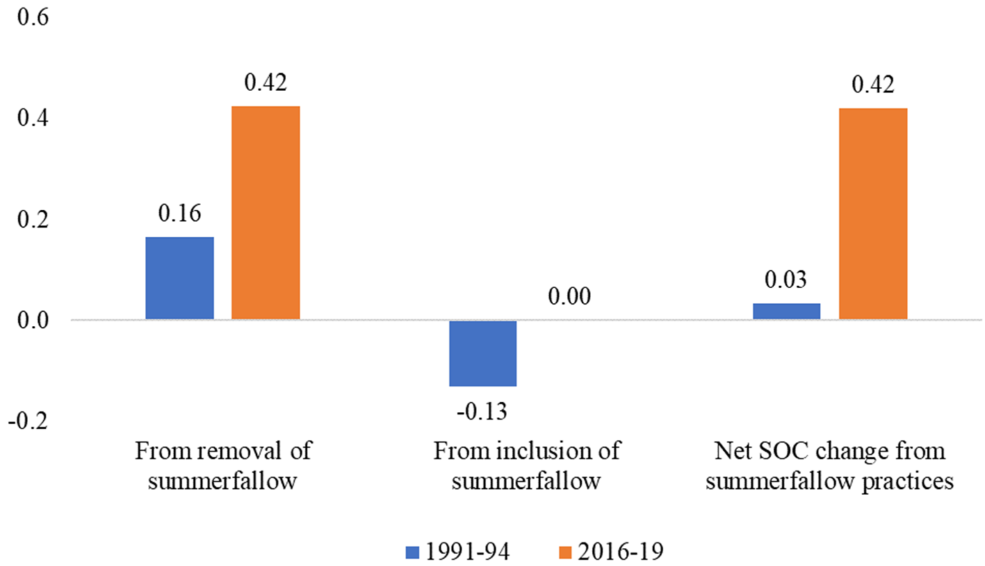

Figure 2. Change in SOC from changes in summerfallow practices (Mg/ha/year).

To put the results of the analysis into context, it is possible to apply the SOC gains per ha to various land aggregates (Table 4).

Table 4. Net SOC gains (Mg/year) from changes in tillage and summerfallow practices.

	From Tillage Practices		**From Summerfallow Practices**	
	1991–1994	**2016–2019**	**1991–1994**	**2016–2019**
1000 Ha Farm	−18.3	119	33.4	421
Total Hectares in Survey Sample (9403 ha)	−172.3	1117	314	3960
Total Saskatchewan Crop Production (15.2 million ha)	−278,624	1,806,192	507,089	6,402,075

If the average sequestration rate were applied to a 1000 ha farm in 1991–1994, this farm would have released 33.4 Mg SOC per year from tillage practices and stored 16.7 Mg SOC per year from reductions in summerfallow practices. By 2016–2019, however, this same farm would be storing 119 Mg SOC per year from the adoption of conservation tillage and 421 Mg per year from the removal of summerfallow. The second row in Table 4 shows the change in SOC from the total hectares in the survey dataset (9403 ha). The bottom row shows the SOC changes applied to the total crop production area in Saskatchewan (15.2 million ha) [52].

By comparison, the average Canadian vehicle annually burns 2000 liters of gasoline and emits roughly 4600 kg of CO_2 [53]. Using the ratio of CO_2 to C (44/12), the average Canadian vehicle emits about 1.25 Mg C annually. A 1000 ha farm in 1991–1994 released 15 times more C than the average car from tillage practices each year, and by 2016–2019 would sequester the emissions from 95 cars from the adoption of conservation tillage practices. Similarly, the annual increase in SOC from this farm in 1991–1994 from the reduction in summerfallow practices would be equivalent to the emissions from 27 cars, and by 2016–2019, equivalent to the emissions from 337 cars.

4. Discussion

The results indicate that the substantial changes in Saskatchewan crop farmers' land management practices over the past 30 years were facilitated by the adoptions of GMHT technology and widespread use of the complementary chemical, glyphosate. These results correspond to previous research quantifying the sustainability benefits following the adoption of GMHT cropping technologies [1,7,10,15,16]. Attribution values of 7.3 and 9.0 out of 10 assigned to HT canola and glyphosate, respectively, indicate that farmers perceive these technologies as crucial to their sustainable adoptions since 1995, and the continued maintenance of these practices. The improved weed control contributed by these technologies provided farmers with an increased opportunity to reduce or eliminate tillage and summerfallow practices, which aligns with previous evidence [1,15,18,19]. Farmers indicate that, without the availability of HT technology, hectares managed with summerfallow would increase from 1% to 23%, representing a decrease in annual sequestration from Saskatchewan soils of about 2.2 million Mg SOC.

These shifts in management practices have contributed to improved SOC levels, which, in turn, contribute to reductions in net GHG emissions. Farmers' widespread adoption of carbon-capturing practices has resulted in the increased annual carbon sequestration of 0.14 Mg/ha from reductions in tillage practices and 0.39 Mg/ha from reductions in summerfallow practices over the past 25 years. Based on farmers' survey responses, these SOC gains would not have occurred to the same extent, and may not have been maintained in the long-term, without the complementary adoptions of GMHT crops and glyphosate. The results observed in Saskatchewan following the adoption of GMHT crops correlated with similar studies conducted in other GMHT crop adopting countries [12–16].

The annual SOC gains in 2016–2019 from reductions in tillage, 0.12 Mg/ha, and from reductions in summerfallow, 0.42 Mg/ha, lie within the estimated ranges of annual SOC gains from previous literature [3,4,26,28]. The estimated SOC gains from reductions in tillage align with the estimates by Grant et al. [27] for SOC gains from NT when their values are converted from Mg CO_2 equivalents to Mg SOC using the ratio of the molecular weight of CO_2 to C (44/12). However, the gains from the reduction in summerfallow estimated in this study are well above the SOC gains from summerfallow elimination estimated by Grant et al. [21]. The authors indicate that their model has some difficulty in generating crop production values in western prairie soils and might underestimate carbon sequestration when moving towards more intensive crop rotations. Estimated increases in annual SOC gains from summerfallow elimination in this study are also higher than estimates from Sperow [29]. However, as this study was conducted on agricultural soils in the United States, regional differences might affect the estimated sequestration results.

In a similar emission quantification analysis on Saskatchewan agricultural soils in 2018, Smyth and Awada [25] estimated between 1990–2016, Saskatchewan's annual sequestration increased by 8.32 million Mg CO_2 equivalents from changes in tillage and summerfallow practices. Using the ratio of CO_2 to C (44/12), this equates to 2.27 million Mg SOC. These results align well with the estimated increase in annual Saskatchewan SOC gains of 2.08 million Mg SOC from reductions in tillage presented in this study. However, the increase in annual SOC gains from reductions in summerfallow estimated in this study, 5.89 million Mg SOC between 1991–1994 and 2016–2019, is much higher than Smyth and Awada's estimates.

There are several differences between this study and that of Smyth and Awada [25]. Data for their study was gathered from a variety of sources, including Statistics Canada and various industry surveys, unlike the present study, which collected all data from one subset of Saskatchewan farmers. Furthermore, in the survey sample used for the present analysis, the average participant was younger and operated larger farms than the average farmer in Saskatchewan. Previous research suggests that younger farmers and those operating larger farms might be more likely to adopt innovative practices such as NT [47,48]. The carbon coefficients chosen for Smyth and Awada's analysis were synthesized from empirical literature and combined the effects of tillage and summerfallow reductions, unlike those used in this study that present the effects from these cropping activities separately. In addition, due to the absence of data on residue removal techniques in Smyth and Awada's study, the conservative assumption that only residue levels above 3.33 Mg/ha contribute positively to carbon sequestration was required to account for baling or burning of crop residues. In this research, survey participants reported on their residue removal techniques, dismissing the need for this assumption. The distinctions between the studies may explain the differences in sequestration results from summerfallow practices to some extent.

The Prairie Soil Carbon Balance project, initiated by the Saskatchewan Soil Conservation Association, also attempted to monitor changes in SOC levels across Saskatchewan due to changes in land management practices between 1996 and 2018 [6]. A network of 136 commercial farm fields in Saskatchewan were monitored using soil sampling techniques; however, the number of fields monitored varied throughout the project as farm operators changed. Their results found moderate and variable changes in SOC levels, with the average increase in SOC over this time period being roughly 5% of initial SOC levels from reductions in tillage and summerfallow. This estimate is much lower than the results presented in the present analysis. Their results were limited by a lack of management data at many of the sites throughout the project. In addition, high spatial variability within benchmarks made it difficult to measure changes in SOC levels for individual fields.

In 2019, GHG emissions from Canada's agricultural sector were estimated to be 73 million Mg CO_2 equivalents, representing about 10% of Canada's total national GHG emissions [54]. Using the ratio of CO_2 to C, this results in about 20 million Mg SOC. Comparing Canada's total agricultural emissions to the 2016–2019 annual gains in SOC in Saskatchewan presented in this analysis, 1.81 million Mg from reductions in tillage and 6.4 million Mg from the removal of summerfallow, the annual SOC gains represent 9% and 32%, respectively, of Canada's emissions from the agricultural sector.

In the Paris Accord, Canada committed to reducing national GHG emissions to 30% below 2005 levels by 2030. Using the 2005 annual emission estimate of 730 million Mg CO_2 equivalents, a 30% reduction requires emissions to be reduced by 219 million Mg CO_2 equivalents, or 59.72 million Mg C, by 2030 [55]. Based on the results of this analysis, C sequestration in Saskatchewan agricultural soils is annually contributing 2–11% of Canada's required national emission reductions.

5. Conclusions

Total positive emissions were not examined in this analysis, and therefore the results cannot be used to comment on the total changes in net emissions from prairie dryland crop production. Further research into total emissions is required to quantify the net contributions to Canada's emission reduction goals. However, the results show the importance of including net C sinks, as well as sources, in emission calculations. Considering that these results only represent carbon sequestration in one province, they also indicate that beneficial land management practices of Saskatchewan dryland crop farmers are helping to offset a significant portion of the positive emissions from Canada's agricultural sector. Through the virtually complete adoption of sustainable soil management practices, facilitated by innovative tools and technologies, including HT cropping systems and the associated chemicals, Saskatchewan crop farmers are reducing the carbon footprint of their operations and contributing to Canada's important climate objectives.

This research confirms the essential contributions to improving agriculture's sustainability made by GM crops and glyphosate, providing insights into the challenges facing jurisdictions that anticipate increased carbon sequestration without either technology or certainly significant restrictions on each technology. Saskatchewan farmers have confirmed just how crucial the use of glyphosate is with the complementary technology of HT crops for the ability to continuously maintain sustainable land management practices. Removing or restricting either or both of these technologies would have adverse impacts on sustainability.

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