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Assessing Saskatchewan forage production with regard to carbon and nitrogen emissions

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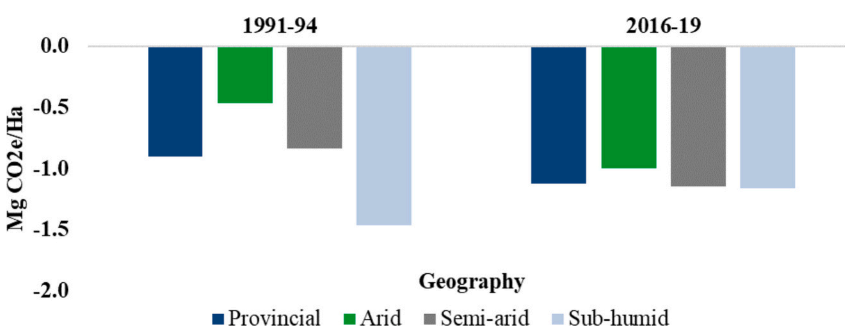
HIGHLIGHTS

- Fall fertilizer applications have fallen by 50 %.
- Forage legume production has increased by 20 %.
- CO_2 sequestration has risen from 0.0006 to 0.123 Mg/ha/yr.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Policy issues in most nations include adapting primary agricultural production to reduce greenhouse gas (GHG) emissions. Commitments have been established through multi-lateral agreements targeting GHG emission reductions to abate climate change impacts. In response to policy initiatives targeted at industries such as agriculture, producers are adopting innovative production methods and technologies to provide environmental services and mitigate emissions. GHG emissions arising from livestock production contribute to a damaging narrative surrounding agriculture, particularly beef production.

OBJECTIVE: The purpose of this study is three-fold, quantifying (a) net emissions,[2] (b) changes in practice, and (c) economic outcomes attributed to the forage production facet of cow-calf production.

METHODS: The Saskatchewan Forage Production Survey was developed to gather forage management practices data, placing emphasis on land use and land management changes. Canada's whole-farm assessment model, Holos, was applied as a carbon accounting framework to derive the net emissions of the forage production cycle.

RESULTS AND CONCLUSIONS: Results indicate carbon sequestration increased between the periods of 1991–94 and 2016–19. Gross emissions decreased to a larger degree and net emission results for the forage production facet of the Saskatchewan cow calf sector are −0.123 Mg CO2e/ha/yr in 2016–19.

SIGNIFICANCE: Recommendations include the renewal of forage rejuvenation funding programs that may improve forage yields and carbon sequestration potential. Further, the expansion of term conservation easement programs to include non-native forage lands is recommended to incentivize the retention of forage land.

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[2] Net emissions are calculated as gross emissions less carbon sequestration as soil carbon storage.

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1. Introduction

Key policy issues in most nations involve facets of environmental sustainability, the mitigation of climate change, and agri-food system resilience. International commitments have been established targeting greenhouse gas (GHG) emission reductions. Stemming from these commitments are domestic policy initiatives including cost-sharing programs, carbon taxes, and GHG offset systems intended to incentivize behavioural changes of economic actors for environmental and climatic betterment. Concurrently, ensuring food security in the least developed nations is a vital societal objective and a top Sustainable Development Goal, necessitating a 25–70 % augmentation of existing food supplies (Wuepper et al., 2020).

Primary agricultural production is foundational to food production and will be central to addressing this century's most formidable challenges. In response to policy initiatives targeted at GHG-emitting industries like agriculture, producers adopt innovative production methods to provide environmental services[3] and mitigate GHG emissions. The adoption of best management practices (BMPs)[4] facilitates the growth of agricultural productive capacity without imposing harm on environmental indicators or increasing GHG emission intensity.

The provision of public funds in cost-sharing programs is increasingly used to proliferate BMP adoption rates. Financial rebates for the implementation of BMPs is a policy intervention common to numerous developed agriculturally based economies (Chouinard et al., 2008; Liu and Brouwer, 2022); however, Canadian cow-calf producers remain cautious, often hesitant to adopt new ideas without observing peer success (Davidson, 2019). GHG emissions arising from input use and machine operation contribute to a damaging narrative surrounding beef production (Pierrehumbert and Eshel, 2015). Subsequently, if consumer and policy maker attitudes towards the cow-calf industry become largely negative concerning the environmental impact of beef production, future development of the industry may be hindered. If an environment characterized by low public acceptance becomes prominent, the industry will be unable to flourish for two core reasons. The first is the inability to utilize productivity enhancing technologies or practices if acceptance levels of the technology or industry are low (Yvonne, 2021). The second detriment arises when an unfavourable regulatory environment fuelled by public dissidence results in harmful input bans or costly changes to production systems (Yvonne, 2021).

Innovative technologies and sustainable production methods can maintain consumer trust in beef production by reducing net GHG emissions and mitigating environmental impacts. Forage production holds high carbon sequestration potential; however, emissions must also be considered for a comprehensive environmental assessment. Western Canadian cow-calf producers heavily rely on forage to sustain breeding stock herds, making forage production pivotal in the sector (Schoofs and Entz, 2000).

The purpose of this study is three-fold, building upon existing literature by quantifying (a) net emissions, (b) changes in practice, and (c) the non-market value of stored SOC in the forage production facet of the Saskatchewan cow-calf production cycle. The use of survey results in combination with Holos – Canada's whole-farm emissions assessment model – contribute to achieving these objectives.

2. Background

Global GHG emissions and environmental pollution stemming from agriculture must be considered at the advent of any attempt to intensify food production (Entz et al., 2015; Franco et al., 2021; Thorup-Kristensen et al., 2020; Wuepper et al., 2020). Beusen et al. (2016) cite primary agricultural production as the principal source of nutrient pollution in surface water globally. Moreover, farm-level GHG emissions stemming from tillage, fertilization, and machinery use are perceived as sizeable contributors to global climate change (Beusen et al., 2016). Nonetheless, the Intergovernmental Panel on Climate Change (IPCC) touts agricultural land as being of great importance in combatting climate change (IPCC, 2022). Canadian Prairie grasslands and perennial forage stands[5] have significant potential to improve environmental outcomes while mitigating carbon (C) and nitrogen (N) emissions through increased soil storage (Balesdent et al., 2018; Follett and Reed, 2010; Silva et al., 2022).

Within Saskatchewan, there are 11 distinct and diverse eco-regions (Canadian Plains Research Centre [CPRC], 2007; Cota-Sanchez, 2006), of which, four are agriculturally based. Eco-regions in the province span from northwest to southeast following the precipitation gradient that drives climatic conditions in each region (CPRC, 2007). The predominant agricultural eco-regions of Saskatchewan are the Boreal Transition, Aspen Parkland, Moist Mixed Grassland, and Mixed Grassland regions (CPRC, 2007). The Boreal Transition and Aspen Parkland are characterized as sub-humid, with the Moist Mixed Grassland and Mixed Grassland regions considered semi-arid, and arid respectively (Cota-Sanchez, 2006). Fig. 1 displays the boundaries of these eco-regions based on the prevailing climatic classification. Differences in climate and soil type affect the rate of soil carbon sequestration (SCS).

Source: Adapted from Mkhabela et al. (2011).

Forages are defined as any vegetative growth consumed by animals via grazing, as dry matter, or as ensiled preserved feed (Beef Cattle Research Council [BCRC], 2022; Ontario Ministry of Agriculture Food and Rural Affairs [OMAFR], 2022). Forages are a vital component of the western Canadian cow-calf sector, comprising upwards of 90 % of animal intake (Entz et al., 2002). A diverse selection of forage crops, including perennial grasses, legumes, and annual crops, are used for conserved forage in western Canada.

Table 1 outlines four grassland management systems that broadly encompass forage production in the Saskatchewan cow-calf sector.

Globally, 3.6 billion hectares (ha) are under the consistent cover of grassland or perennial forages, accounting for 25 % of the global soil C storage capacity (Follett and Reed, 2010). This vast carbon sink remains despite the expansive losses of temporary and permanent forage lands. Prior to 2010, approximately 20 % of the world's grassland had been converted to arable land (Conant et al., 2017). A meta-analysis conducted by Guo and Gifford (2002) found the conversion of grassland to cropland can result in a 58 % loss in sequestered soil carbon. Soil organic carbon (SOC) is the principal component of soil organic matter (SOM), a factor known to dictate the fertility and efficiency of agricultural soils (Lal, 2016; Maillard et al., 2018). Since 1990, the amount of area under cover from perennial tame forages or native grassland has steadily declined in Saskatchewan, with estimates of lost forage acres totalling nearly 1.5 million hectares in the 25 years post-1990 (Doke Sawatsky, 2018). A decrease of 367,216 ha occurred between 2011 and 2016 alone, with an additional 1,656,502 ha being dedicated to crop production during this time (Government of Saskatchewan, 2023a). Fig. 2 illustrates lost tame forage acres based on Statistics Canada data, with corresponding increases in canola acreage. This shift can be attributed to technological and agronomic advancements enabling profitable crop production on lands of lesser productive quality.

Land that presents significant barriers to crop production is designated marginal land, and has become arable through recent agronomic, technological, and engineering advancements (Esch et al., 2021; Lawley, 2019). Increasing returns from crop production relative to livestock

[3] Environmental services are positive externalities that maintain natural resources for human and wildlife habitation (Follett and Reed, 2010).

[4] Methods of agricultural production that harmonize productivity, environmental stewardship, and business goals to improve economic outcomes without harming natural resources are termed BMPs (Government of Ontario, 2022).

[5] Forage stands are fields planted to perennial species dedicated to producing forage in consecutive years.

production have contributed to this change (Lawley, 2019). However, the relative efficiency of marginal land in crop production is highly variable, with crop production on marginal land requiring greater input use to garner profitable yield rates (Esch et al., 2021; Lawley, 2019).

The over-utilization of marginal land for crop production can have harmful impacts on economic performance (Esch et al., 2021), environmental service provision (Lawley, 2019), and soil GHG sequestration capacity (Csikós and Tóth, 2023). The growth of green vegetative mass facilitates carbon sequestration by removing carbon dioxide (CO_2) from the atmosphere and storing it as SOC (Follett and Reed, 2010). Much of the increase in SOC arises from the decomposition of plant roots and litter into the soil profile (Mapfumo et al., 2002). Hence, forage stands that are only harvested once per annum may generate greater volumes of above ground leaf and stem litter enabling a faster rate of SOC accumulation (Grant et al., 2020).[6] Increases in SOC translate to lower atmospheric carbon levels; however, numerous other benefits to soil properties stem from expansions to SOC pools (Blanco-Canqui et al., 2013). Specific SOC-stimulated benefits include improved water holding capacity and infiltration rates, higher levels of nutrient cycling, and improved soil productivity, translating to higher yields and further increases in SOC stocks (Blanco-Canqui et al., 2013).

Constant development of root and plant biomass throughout the growing season in permanent forage systems and the opportunity to incorporate multiple species on one land parcel are known to improve the carbon content of agricultural soils (Fernandez et al., 2019; Franco et al., 2021; Gamble et al., 2019; Singer et al., 2009). Soil organic content is directly related to the volume of plant litter and root biomass (Conant et al., 2017; Guo and Gifford, 2002; Mapfumo et al., 2002). As such, yield and rooting characteristics of forage species are two factors that greatly influence GHG sequestration capacity. Estimates of the carbon sequestration capacity of perennial forages is 0.55 and 0.56 Mg/ha/yr in semi-arid and sub-humid Canadian regions, respectively (VandenBygaart et al., 2008). Robust C sequestration rates stem from the complimentary growth patterns of varying grasses and legumes included in forage stands; however, management factors also influence C sequestration rates.

Desjardins et al. (2007) modelled cumulative carbon sequestration

Table 1
Grassland management systems common to Saskatchewan.

Grassland Management System	Use	Duration
Permanent Forage		
Prairies	Preserved forage (fodder)	Continuous
Pastures	Direct grazing	Continuous
Temporary Forage		
Rotational Systems	Grazing or fodder	1–15 years
Integrated Systems	Grazing, fodder, or extensive winter feeding	<1 year

Source: Adapted from Chabbi et al. (2022).

and emission reductions by introducing a variety of production practices on land managed by conventional tillage, finding significant sequestration potential in grasslands. Six treatments were explored: 50 % fertilizer volume, 150 % fertilizer volume, no-tillage adoption, perennial forage system adoption, reduced summer fallow, and forages in rotation.[7] Results indicated that commonly cited practices such as reducing summerfallow or lessening tillage intensity would result in sizable increases in GHG sequestration potential with corresponding reductions in CO_2 and N_2O emissions. However, the practice with the greatest impact on net emissions was switching from annual cropping to a permanent forage system (Desjardins et al., 2007).

Table 2 displays the findings of Desjardins et al. (2007), adapted to Mg CO_2e/ha/yr., highlighting the importance of grassland in sequestering GHGs.

Efforts to guide land use towards net emission reducing agricultural practices is not a new issue, with early policy interventions fuelled by public disdain occurring as far back as the 1980s (Cary and Wilkinson, 1997). However, producer perceptions of the technical and economic viability of BMPs are often at odds with societal expectations. Facilitating the adoption of practices often requires regulatory intervention to meet conservation goals while ensuring the viability of the agricultural sector. Instruments available to policy makers to promote adoption include expenditures on infrastructure and educational provisions. Further, monetary incentives, regulatory frameworks, and moral sua-

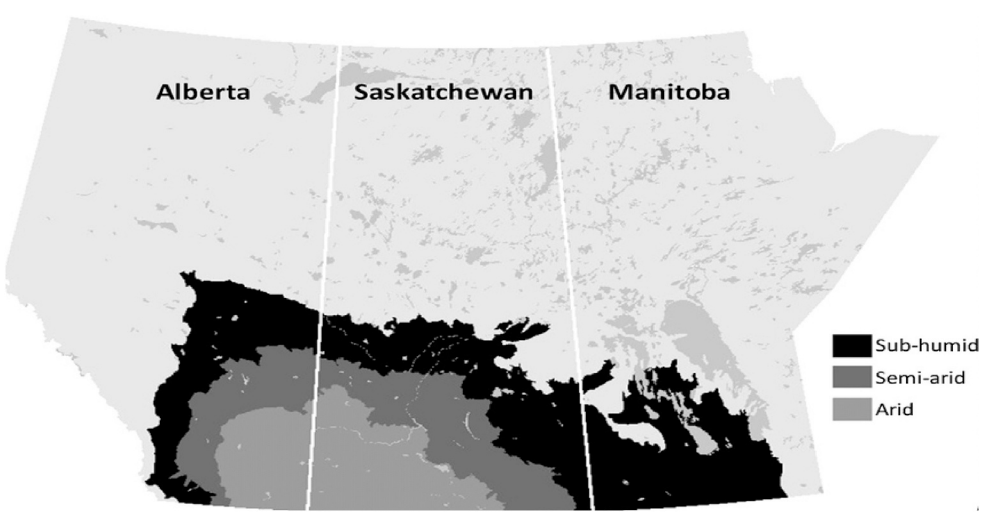

Fig. 1. The agricultural eco-climatic zones of Saskatchewan.

[6] Dryland forage production typically only allows for one cut per year. In high rainfall years, it is possible for dryland farmers to get a second cut. This is compared to irrigated forage production that is able to generate multiple cuttings.

[7] 50 % fertilizer denotes half of recommended fertilizer application rate.

sion can serve to drive adoption (Cary and Wilkinson, 1997).

Producer-public cost-sharing for the implementation of BMPs is utilized to proliferate adoption rates at the farm level. Reducing farm-level expenditures via cost-share programs is a policy intervention common to numerous developed agriculturally based economies (Chouinard et al., 2008; Liu and Brouwer, 2022). In Saskatchewan, the On-Farm Climate Action Fund and Resilient Agricultural Landscapes Program provide producers with multiple cost-sharing alternatives for BMP implementation. Rejuvenating existing perennial forage systems, converting annual crop land to perennial forage systems and adopting practices that reduce nitrogen emission potential are all included in cost-sharing programs within Saskatchewan (Government of Saskatchewan, 2023b). As demonstrated by the literature to date, proper management of forage systems and the conversion of annual cropping to perennial forage systems may increase SCS potential. However, many BMPs increase production risk and provide negative returns in the initial years; however, providing public funds to producers may make these BMPs economically feasible when implemented. Nonetheless, significant public funds are required to implement such interventions (Chouinard et al., 2008; Fleskens et al., 2022; Liu and Brouwer, 2022). Financial gain is seen as the primary driver of the adoption of innovative technologies in agriculture; as such, much of the literature has been focused on identifying mutually beneficial policies whereby no economic concessions are required to foster environmental conservation (Chouinard et al., 2008; Possberg, 2016; Wuepper et al., 2020). Figge and Hahn (2012) refute this idea, asserting that win-win policies must not be the focus of policy makers. Rather, the authors propose that a combination of policies that provide maximum environmental gain with minimal economic detriments would better utilize public funds. Synchronously, policies that create excessive amounts of economic value while marginally harming environmental value provisions must not be disregarded or prohibited by policy, rather they should be adopted in unison (Figge and Hahn, 2012). The desired result of this concept is maximizing economic value creation per tonne of CO_2 emitted, enabling firms to improve profitability without generating negative environmental externalities.

3. Methodology

The Saskatchewan Forage Production Survey was developed to gather on farm management practices data pertaining to forage production in the cow-calf sector. Emphasis was placed on data relevant to determining land use changes[8] (LUCs) and land management changes[9] (LMCs). Questions were designed to gather metrics relevant to calculating the GHG emissions and SCS impacts of livestock forage production. The seven-part survey gathered data on input use, cropping selection, forage yields, and machine employment, amongst other production practices. Each survey segment integrated two time periods, 1991–94 and 2016–19; however, respondents focused on the same land parcel in each period to control for regional variation in climate, soil type, or other geographically dependent metrics. The survey was open from July 2023 to March 2024.

Recruiting a sufficient sample of Saskatchewan cow-calf producers to complete a survey of the length and breadth characterized by the Saskatchewan Forage Production Survey involved numerous media and in-person marketing campaigns. Surveys were provided to producers in an online format at the beginning of the month that was self-selected as preferable for completion. To compensate for the time expended in completing the survey, producers were offered a $200 honorarium upon completion of the survey in its entirety. The survey was exempt from review by the University of Saskatchewan's Ethics Review Board as the survey collected only data, not respondent perspectives, views, or opinions.

On March 7, 2024, the survey had been attempted by 81 respondents. Of these, 35 were determined to be incomplete or duplicate responses and were omitted from the dataset. 17 farms completed the survey for both time periods, with 29 respondents completing only the

Table 2
Annual net emissions reductions of various agricultural production practices relative to conventional tillage (Mg CO_2e/ha/yr).

Study Site	50 % fertilizer	No-till adoption	Reduced Summerfallow	Perennial adoption
Three Hills, AB	0.086	1.6		**4.0**
Lethbridge, AB	−0.096[a]	0.556	0.41	**3.5**
Swift Current, SK	0.013	0.6	0.426	**3.3**
Harrow, ON	0.08	1.326		**7.2**
STE Foye, QC	0.35	1.556		**7.7**

a: Negative values indicate increases in GHG emission potential.
Source: Data from Desjardins et al. (2007).

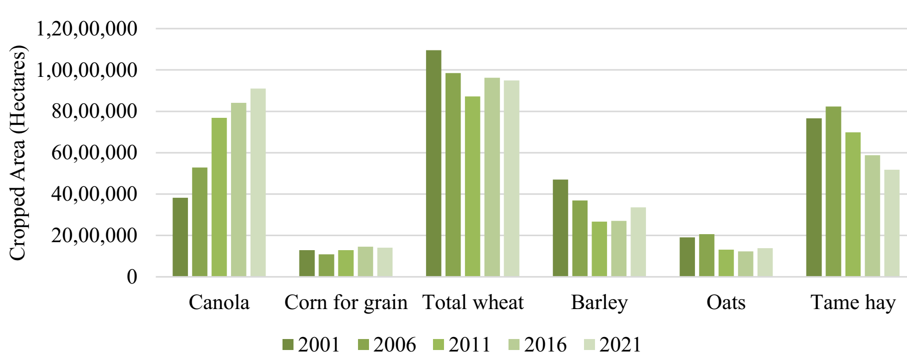

Fig. 2. Changes in land use by commodity in Canada, 2001–2021.
(Source: Adapted from AAFC (2021).)

[8] Land use changes are changes to the production system practiced (e.g., annual to perennial cropping).

[9] Land management changes are changes made while maintain the current agricultural system (e.g., feedlot to extensive feeding, changes in fertilizer application rate or forage rejuvenation).

2016–19 section of the survey. The farms surveyed covered 19,931 ha in 1991–94 and 72,307 ha in 2016–19, with a total of 6930 and 11,102 beef cows cumulatively in 1991–94 and 2016–19, respectively. Relative to the 1.1 million beef cows on 787,000 ha in Saskatchewan (St. Pierre and Mhlanga, 2022), survey respondents are a small subset of beef production. However, the collected data encompasses approximately 2.5 % of cow-calf land use. The collected data provides as reliable and representative a dataset as could be expected given typically low producer response rates to online questionnaires. Substantial analysis of this dataset was undertaken to determine the net carbon emissions of livestock feed production.

Given the sample size of 46 respondents, it is necessary that the demographics of the survey respondents are compared to 2021 census of agriculture demographics to examine the magnitude of difference between respondents and typical Saskatchewan ranchers. Apart from farm size, respondent characteristics align with data from the 2021 census of agriculture. Further, it appears that younger producers were over-represented in the survey, a possible impact of the survey being offered in an online-only format (Table 3).

The postal codes of respondents were compiled through the survey, allowing for approximations of the area in which the respondent operation was located while maintaining anonymity. Fig. 3 displays the geographic dispersion of survey respondents beside the distribution of grasslands within the province, highlighting an alignment between areas of major grassland and survey responses.

3.1. Assumptions

Numerous simplifying assumptions are required to ensure the Holos model produces reliable results. To properly convey the modelling undertaken as part of this research, definitions of tillage intensity must be established. The classifications used in the Holos model will serve as the designations for this article. As such, no till (NT) is defined as an agricultural system involving a single tillage pass for seeding; reduced tillage (RT) is classified as one to three tillage passes with most surface residue retained; and intensive tillage (IT) is designated as multiple tillage passes constituting the complete burial of field residue (Pogue et al., 2023).

Table 3
Survey respondent characteristics compared to 2021 Canadian Agriculture Census.

Demographic Factor	2023 Forage Production Survey	2021 Census of Agriculture
Farm Size (Acres)		
130–759	9 %	48 %
760–1119	7 %	10 %
1120–1599	12 %	9 %
1600–2239	9 %	9 %
2240–2879	16 %	6 %
2880–3519	12 %	5 %
3520 ≤	35 %	14 %
Participant Age		
Under 35	20 %	10 %
35–54	46 %	30 %
55 and over	33 %	61 %
Educational Attainment		
Less than High School	5 %	15 %
High School or Equivalent	47 %	36 %
College or University	47 %	48 %
Collect Off-Farm Income		
Yes	49 %	56 %
No	51 %	44 %

Source: Statistics Canada, 2022.

Carbon saturation, and its impact on soil C sequestration potential, is a fundamental component of SOC modelling. Within the literature, it is perceived that as SOC levels reach a saturation point the rate of soil C sequestration slows (Stewart et al., 2008). SOC saturation levels vary widely with changes in climate, soil type, texture, and a multitude of other factors (Stewart et al., 2008). Holos lessens the accumulation of SOC for specific LUCs and LMCs over time until a saturation or degradation point is reached based upon the prevailing climate, management, and soil texture (Pogue et al., 2023). It is assumed that SOC saturation can and does occur as changes in SOC increase at a decreasing rate until equilibrium.

Other assumptions are classified as agronomic or production related. The first assumption is that fertilizer was applied at the recommended rate (based on crop type, region, and soil type) where the respondent indicated fertilizer application was completed, and details on application rate were not provided. Secondly, modelled yields, based on climatic conditions, crop type, and perennial stand duration, were used when no yield details were provided. Lastly, harvest dates were set as July 15th for perennial forages and August 15th for annual forage crops, based on historical crop reports.

3.2. Holos model

Canada's whole-farm lifecycle assessment tool, Holos, has been widely applied in lifecycle assessment literature to determine the net emissions of beef production in various geographic regions of Canada (Alemu et al., 2017; Beauchemin et al., 2010, 2011). Holos builds upon IPCC Tier 2 methodology, adapting algorithms within the model to geographic differences in climate and soil type characterizing the Canadian landscape (Beauchemin et al., 2010; Pogue et al., 2023). This overcomes the common criticism of using national level reporting methods at the region scale. The primary criticism being the application of highly aggregated coefficients to differentiated soil and climate characteristics. As such, aggregated coefficients may yield inaccurate representations of real-world regional emission levels (Crosson et al., 2011). The purpose of the model is to provide net GHG estimates for individual farms on an annual time step based upon user-entered data specific to the locality and production methods of the agricultural system (Pogue et al., 2023). The algorithms contained in the Holos application are those developed in peer-reviewed literature with a Canadian focus. Following IPCC recommendations, Holos accounts for specific farm-level land use and management practices (Little et al., 2008; Pogue et al., 2023), improving its applicability for the current objectives.

System boundaries must be established to enclose a model of such wide range to the current research objectives. Following the approach of Alemu et al. (2017), system boundaries were established at the end of the production cycle. In differentiating from the work of Alemu et al. (2017), the current model is applied to forage production systems. As such, the system boundary begins at any land preparation or seeding of lands utilized for fodder production within the period of study, 1991–94 or 2016–19. Consequently, the ending boundary will be applied when (a) the end forage product leaves the farm (i.e., is sold to a third party), (b) when the fodder reaches on-farm storage, and (c) when the final field pass is made in preparing feed for extensive winter-feeding systems.

Net emissions from forage production, quantified with a modified version of Holos as a carbon accounting framework is described by Eq. 1. Using the conversion factors outlined in the equation, the Holos framework converts all emission and sequestration factors to CO_2e, enabling simplified and uniform reporting of net emission estimates.

Eq. 1. Annual net emissions from the forage production cycle

$$NE_{(i)} = \sum_{t=1}^{4} \sum_{n=1}^{n} \frac{\Delta SOC_{(t,n)} * 3.67}{1000} - \frac{N_2O_{em(t,n)} * 298}{1000} - \frac{CO_{2cropenergy(t,n)}}{1000}$$

Where:

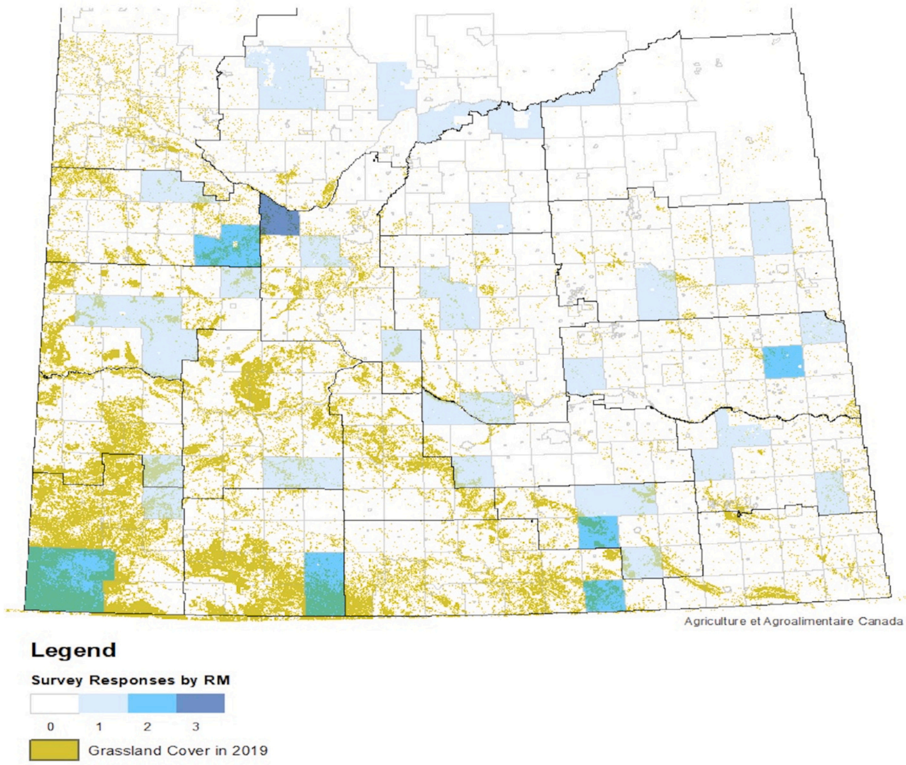

Fig. 3. Survey respondent locations overlayed on a map of Saskatchewan grasslands.

$NE_{(i)}$ = Net emissions of all n field reported on in period i in CO_2e.

$\sum_{t=1}^{4}$ = The sum of the four years in period i.

$\sum_{n=1}^{n}$ = The sum of all n fields reported on in period i.

$\Delta SOC_{(t,n)}$ = Change in soil organic C from time t-1 to time t (kg/ha) in field n.

$N_2O_{em(t,n)}$ = N_2O emissions from all sources (kg N_2O/ha) in year t in field n.

$CO_{2cropenergy(t,n)}$ = CO_2 emissions from fuel use (kg CO_2 /ha) in year t in field n.

Emission coefficients serve as a valuable instrument in the modelling of GHG emissions and sequestration. The direct measurement of long-term emission and sequestration levels across the broad geographic area of the study region would be desirable; however, this is not a feasible technique for the current study. Alternatively, carbon change coefficients aligned with each LUC and LMC under study provide reliable emissions estimates. Within the empirical literature an array of coefficients corresponding to LUCs and LMCs in the Canadian Prairie's exists. However, the wide variation in coefficient values within the literature make it appropriate that the coefficients within Holos be used for the present research. The Holos model employs a multitude of parameters such as crop type, soil zone, moisture balance, temperature, planting date, and harvest date to modify carbon sequestration and emission coefficients like those in Table 4. This enables the model to quantify net emissions for individualized agricultural systems. Table 4 details annual and perennial forage crop-specific coefficients used to estimate CO_2 emissions attributed to tillage intensity in each soil zone within the Saskatchewan.

Table 4
Crop-specific emission coefficients corresponding to tillage intensity.

Soil zone	Black			Brown		
Tillage intensity	IT	RT	NT	IT	RT	NT
CROP						
Fallow	2.35	1.71	0.93	1.62	1.16	0.34
Silage (Corn, Barley, Oat, Triticale, Wheat)	2.63	2.39	1.43	2.02	1.78	1.42
Clover (Red, Berseem, Sweet)	2.63	2.39	1.43	2.02	1.78	1.42
Hairy Vetch	2.63	2.39	1.43	2.02	1.78	1.42
Alfalfa	2.63	2.39	1.43	2.02	1.78	1.42
Ryegrass	2.63	2.39	1.43	2.02	1.78	1.42
Rangeland (native)	2.63	2.39	1.43	2.02	1.78	1.42
Tame forage (grass, legume, mixed)	2.63	2.39	1.43	2.02	1.78	1.42

IT: Intensive tillage, RT: Reduced tillage, NT: No till.
Source: adapted from Pogue et al., 2023.

3.3. Economic valuation of CO_2

Four distinct yet interrelated techniques of valuing carbon fluxes were explored. The literature revealed a high variation in these costs between methods; however, Carbon Capture and Storage, the Canadian Carbon Tax, and carbon exchange markets all operate within a narrow range in Canada. Conversely, the Social Cost of Carbon exceeds this range by multiples of five in some instances, generating an upper bound on emissions valuations. Table 5 is a summary of the emission values used to economically quantify the carbon fluxes generated from forage production in Saskatchewan's cow-calf sector.

Table 5
Summary of economic carbon valuations.

Measure	Value	Source
Social cost of carbon	\$261 Mg^{-1} CO_2	Government of Canada, 2023b
Carbon marketplace	\$22.68 Mg^{-1} CO_2	Government of British Columbia, 2022; Government of Quebec, 2023
Carbon taxation	\$65 Mg^{-1} CO_2	Government of Canada, 2022
Carbon capture and storage	\$46 Mg^{-1} CO_2	Zhang et al., 2023

4. Results and discussion

Substantial changes to forage production practices were observed in the Forage Production Survey. Table 6 details the percentage of reported hectares dedicated to a given practice in each period of study. Results indicate that metrics including perennial forage inclusion, age of forage stand, and land use goals have changed between time periods. However, only the incidence of fall fertilizer applications differed to a statistically significant degree ($p < 0.05$) between time periods. In 1991–94, the average age of tame perennial forage stands was 5.6 years, perennials were included on 85 % of hectares, and summerfallow was practiced on 2 % of hectares. Twenty-five years later, the average forage stand is 8 years old, perennials are included on 90 % of forage land, and summerfallow incidence has decreased to 0.4 % of hectares. Finally, Table 6 provides an in-depth view of the changes exhibited in Saskatchewan forage production across a broad range of metrics based on the percentage of hectares dedicated to each production method.

Using the forage management practices outlined in both time periods at regional and provincial levels modelling of SOC and emissions was conducted to determine the contribution of forage production to environmental sustainability efforts. The IPPC emissions and soil C accounting methodology, contained within the Holos model, was used to estimate changes in SOC, carbon emissions, and nitrogen emissions. Annual net emissions for both periods are presented on a per hectare basis (Fig. 4). As discussed above, net emissions are calculated as total emissions added to the net change on SOC, where sequestration assumes a negative value.

In 1991–94, the net emissions of forage production were negative, indicating that each hectare of land in forage production was storing 0.006 Mg/ha/yr of CO_2e or 0.025 Mg of CO_2e in the four-year period. In the 2016–19 period, each hectare of forage land was responsible for storing 0.123 Mg/ha/yr of CO_2e and 0.493 Mg of CO_2e for the four-year period. This represents a decrease in net emissions of 0.468 Mg/ha over the 25 years between periods of study.

Disaggregating these estimates into regional net emission values provides further insight as to the regional differences in C sequestration and SOM decomposition. In 1991–94, the arid eco-region of Saskatchewan had the most favourable net emissions estimate of −0.214 Mg CO_2e/ha and improved substantially to −0.998 Mg CO_2e/ha in the four years encompassing 2016–19. However, this improvement was overshadowed by the progression of the semi-arid region of the province between time periods. In the semi-arid eco-region, each hectare of land contributed to emissions in 1991–94; however, by 2016–19 each hectare of land was a net sink of 0.611 Mg CO_2e/ha, or 0.152 Mg CO_2e/ha/yr. This reversal may be attributed to changes in the proportion of hectares dedicated to legumes, or mixtures including legumes, which grew from 68 % to 94 % between time periods. Each hectare of land in the sub-humid region was assigned a net emission estimate of −0.139 Mg CO_2e/ha (0.347 Mg CO_2e/ha/yr.) in 1991–94. This estimate grew modestly to −0.322 CO_2e/ha (−0.081 CO_2e/ha/yr.) in the 2016–19 period.

Table 6
Percentage of ha. devoted to certain forage production practices (survey respondents).

Production Attribute	1991–94 Average	2016–19 Average	Percentage Point Change	P-value
Summerfallow Hectares	2 %	0.4 %	−1.7	0.14
Legume Hectares	71 %	91 %	+19.5	0.47
Perennial Hectares	85 %	90 %	+4.5	0.88
Fertilizer Application	59 %	63 %	+3.8	0.96
Fall Fertilizer Application	53 %	3 %	−49.8	0.03
Stand Age	5.6	8		0.11

Changes in SOC are presented separately from emissions to illustrate the impact of forage production on this C sequestration alone (Fig. 5). It was expected that net emissions would be lowest in the sub-humid region as SCS potential is higher in this region. However, this was not the trend seen in the modelling outputs, as the sub-humid region is the second-highest net-emitter in 1991–94 and held the highest net emissions value in the later period. Net emissions values in the sub-humid ecoregion are primarily driven by higher emission values in this jurisdiction. As illustrated in Fig. 5, carbon sequestration values are highest in the sub-humid region throughout both time periods. In contrast with the arid and semi-arid ecoregions, the annual rate of C sequestration decreases between time periods in the subhumid area of the province. No causal or directly correlative reason for this was evident in the data; however, below average rainfall amounts in the region during the 2016–19 period could not be ruled out. Nonetheless, the sub-humid ecoregion remains a net sink in the 2016–19 period.

Examining the change in SOC per annum provides results similar to that of the net emissions estimation; however, the values are much larger when emissions are excluded. On average, results indicate that each hectare of forage land stored an average of 0.907 Mg of CO_2e in the four years comprising the 1991–94 period. In 2016–19, similar parcels of land are expected to store 1.124 Mg of CO_2e per ha, representing an increase in C sequestration of 0.217 Mg CO_2e/ha. Annualizing the results, provincial estimates for C sequestration are 0.226 Mg CO_2e/ha/yr. for the 1991–94 period and 0.281 Mg CO_2e/ha/yr. during 2016–19.

Results indicate that C sequestration estimates follow the precipitation gradient that differentiates the eco-regions under study. This trend is readily evident in 1991–94 and still present in 2016–19 despite a narrowing of the gap in SCS between ecoregions. Results display a substantive increase in SCS; however, the greater change between time periods remains with net emissions, implying that decreases in emissions outpaced increases in SCS. A summary of average C sequestration, net emissions, and gross emissions is provided in Table 7, displaying emission decreases between periods in all regions except the arid ecoregion.

4.1. *Forage management practices as indicators of net emissions*

To fulfil the research objective of establishing if, and to what degree, these BMPs can be attributed to increases in forage productivity and decreases in net emissions, a cross tab analysis is performed. Grouping the farms into high and low net emission farms, using 0 Mg CO_2e/ha as the threshold, provides a distribution of 57 % high emission and 43 % low emission farms for 1991–94. While 35 % and 65 % of farms are grouped into high and low net emission farms for 2016–19, respectively. Low emission farms are assigned a binary value of 1 for the purpose of this analysis while high emission farms are coded as 0.

Interactions between a variety of farm metrics and resulting emissions classifications are displayed in Table 8. The closer the interaction variable is to 1, the higher the likelihood that the production practice associated with that variable is connected with a low emission farm. The inverse is true for values near zero. Farm characteristics in the analysis are farm size and farmer education level. Production characteristics analyzed include fertilizer incidence, years of perennial and legume inclusion, and stand age. Each interaction is subject to an analysis of variance to determine if results vary with statistical significance at the 95 % confidence level.

Perennial inclusion rates of less than or equal to two years and greater than two years were separated. Coefficients in the 1991–94 period differ in a manner aligned with expectation but without statistical significance. Contrarily, the coefficients for 2016–19 differ to a greater degree, implying that those who include perennials for a greater proportion of time than annuals achieve lower emission intensity. Further, both perennial inclusion groupings display an increased likelihood of being a net sink of C when comparing the 2016–19 coefficients to those derived for 1991–94.

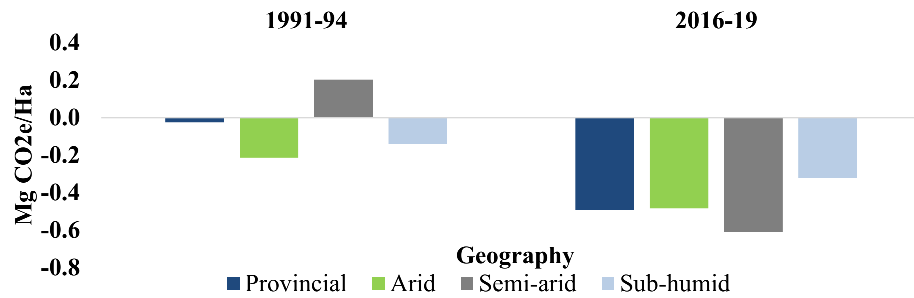

Fig. 4. Annual average Saskatchewan net emissions provincially and by ecoregion (Mg/ha.)

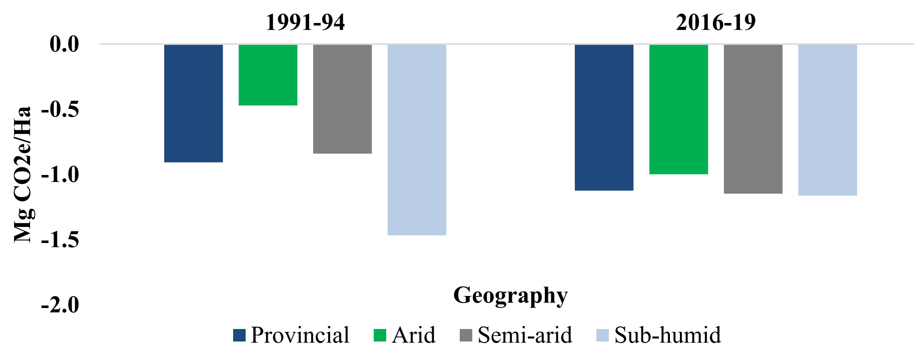

Fig. 5. Saskatchewan soil carbon sequestration provincially and by ecoregion.

Table 7
Net emission, SCS, and emission estimates provincially and by region.

Mg CO_2e/ha/yr	Annualized 1991–94	Annualized 2016–19
Provincial	$n = 23$	$n = 43$
Gross Emissions	0.220	0.158
C Sequestration	−0.227	−0.281
Net Emissions	−0.006	−0.123
ARID	$n = 6$	$n = 8$
Gross Emissions	0.064	0.129
C Sequestration	−0.118	−0.250
Net Emissions	−0.054	−0.121
SEMIARID	$n = 11$	$n = 21$
Gross Emissions	0.261	0.134
C Sequestration	−0.210	−0.287
Net Emissions	0.051	−0.153
SUBHUMID	$n = 6$	$n = 14$
Gross Emissions	0.303	0.210
C Sequestration	−0.367	−0.291
Net Emissions	−0.035	−0.081

Legume inclusion interaction variables provide similar results with one exception. That being, the emissions classification of those including legumes for less than two years declined across time periods, indicating that these farms perform worse from an emissions standpoint in the more recent period. One possible explanation for this finding is an increase of annual legumes as silage crops in 2016–19, another being a higher incidence of perennial crops excluding legumes in the earlier period. The former would reduce sequestration potential and increase emissions according to the findings reported here while the latter would reduce the emissions intensity of crops including legumes for less than two years.

As shown in Table 6, the number of forage hectares receiving fertilizer in Saskatchewan increased modestly between time periods. However, Table 8 displays considerable changes in emission intensity associated with fertilizer application. In the 1991–94 the application of fertilizer lessened the probability that a farm would be classified as low emissions to a significant ($p < 0.05$) degree. In 2016–19, the emissions classification of those who applied fertilizer does not significantly differ from that of those who did not apply fertilizer. Further, the classifications of those who applied fertilizer in 1991–94 differs from 2016 to 19 with significance ($p < 0.10$) while no significant differences exist for those who applied fertilizer in both periods.

Table 8
Interaction between forage production metrics and emissions intensity.

	Emissions Classification Average	
Production Characteristics	1991–94	2016–19
Perennial inclusion		
≤ 2 Years	0.17	0.29*
> 2 Years	0.53	0.69*
Legume inclusion		
≤ 2 Years	0.30	0.20*
> 2 Years	0.54	0.69*
Fertilizer use		
Yes	0.20*	0.58
No	0.62*	0.74
Stand age		
≤ 4 Years	0.50	0.88*
4–7 Years	0.33	0.60*
8–11 Years	0.33	0.17*
12–15 Years	*No responses*	0.63*
>15 Years	1.00	0.67*

*Indicates statistical significance at the 95 % confidence level.

Minimal differences in the age of perennial stand were observed between time periods; however, the interaction between stand age and emission classification are statistically different ($p < 0.05$) in the later period. Results fall in line with prior expectations given that the most recently established forage stands provide the greatest likelihood of a low emission classification. Additionally, the oldest stands, which include those sown to native species, are expected to contribute to lowering emission intensity. Finally, a variety of management practices may influence emission intensity of Saskatchewan forage production and the insights gathered will provide an ample basis for further recommendation.

4.2. Economic valuation of SOC changes

Both net emissions and SOC fluctuations associated with Saskatchewan forage production have been estimated; as such, CO_2 values can be used to derive economic values for the sequestration that has occurred during the periods of study. Given that results are reported in CO_2e throughout this section, the values can be directly applied to net emission and net SOC fluctuation estimations (Table 9).

The results in Table 9 indicate that net emissions in the four-year period spanning 1991–94 have created between $0.57/ha to $6.61/ha depending on the method of valuation. Identical valuation techniques provide a range of $11.18/ha to $128.72/ha for the 2016–19 period. Accumulation of SOC in the earlier period has yielded values ranging from $20.57/ha to $236.76/ha for SCC and the carbon marketplace, respectively. Values assigned to SOC built during the later period of study range from $25.50/ha to $293.41/ha.

Table 10 provides aggregate non-market values for soil carbon storage for the four years comprising each period of study. The volume of per hectare carbon storage as estimated by the Holos model is extrapolated to a 500 ha plot, the total number of hectares reported on in the forage production survey and all land used for forage production in the province of Saskatchewan. The C values outlined in Table 5 are multiplied by modelled carbon storage amounts to derive these estimates. Between periods of study, the economic value attributed to forage production on 500 ha of land, when considering net emissions, increase by a magnitude of C$3801 to C$43,730 depending on the measure used. The estimates of C sequestration are subject to similar rigour with results indicating that cow-calf producers operating on 500 ha of forage lands generated an additional C$93,947 at the bottom of the range and C$1,081,131 at the top. Values increase substantially as the volume of acres increases, with the high range for all hectares reporting forage production in Saskatchewan being nearly C$1.5 billion in the 2016–19 period (Table 10). These values are conservative for cow-calf production as whole, given that native grasslands are omitted from this figure.

4.3. Forage production cost-share programs

The Sustainable Canadian Agricultural Partnership (SCAP) has provided a cost-sharing program network that is available to both crop and livestock producers in the province of Saskatchewan (Government of Saskatchewan, 2023b). The current rendition of SCAP provides

Table 9
Values assigned to net emissions and soil C sequestration, 1991–94 and 2016–19.

Measure	Net Emissions Value/ ha	C Sequestration Value/ ha
1991–94		
Social cost of carbon	$6.61	$236.76
Carbon marketplace	$0.57	$20.57
Carbon taxation	$1.65	$58.96
Carbon capture and storage	$1.17	$41.73
2016–19		
Social cost of carbon	$128.72	$293.41
Carbon marketplace	$11.18	$25.50
Carbon taxation	$32.06	$73.07
Carbon capture and storage	$22.69	$51.71

Table 10
Gross economic value of net emissions and C sequestration.

Net Emissions	1991–94	2016–19	Change
500 ha forage lands			
SCC	$1838	$45,578	$43,740
Carbon marketplace	$160	$3961	$3801
Carbon taxation	$458	$11,351	$10,893
CCS	$324	$8033	$7709
Total ha Reported in Study	7089	12,146	5057
SCC	$26,055	$1,107,186	$1,081,131
Carbon marketplace	$2264	$96,211	$93,947
Carbon taxation	$6489	$275,736	$269,247
CCS	$4592	$195,136	$190,544
SK Tame Forage Land	3,720,616	5,104,692	1,384,076
SCC	$24,596,504	$657,055,950	$632,459,446
Carbon marketplace	$2,137,351	$57,095,896	$54,958,545
Carbon taxation	$6,125,566	$163,634,623	$157,509,057
CCS	$4,335,016	$115,802,964	$111,467,948
Carbon Sequestration	**1991–94**	**2016–19**	**Change**
500 ha Forage Lands			
SCC	$118,378	$146,704	$28,327
Carbon marketplace	$10,287	$12,748	$2461
Carbon taxation	$29,481	$36,536	$7055
CCS	$20,863	$25,856	$4992
Total ha Reported in Study	7089	12,146	5057
SCC	$1,678,387	$3,563,763	$1,885,375
Carbon marketplace	$145,846	$309,679	$163,833
Carbon taxation	$417,989	$887,527	$469,538
CCS	$295,808	$628,096	$332,288
SK Tame Forage Land (Ha)	3,720,616	5,104,692	1,384,076
SCC	$880,874,972	$1,497,759,338	$616,884,367
Carbon marketplace	$76,544,998	$130,150,122	$53,605,124
Carbon taxation	$219,374,993	$373,005,199	$153,630,206
CCS	$155,249,995	$263,972,910	$108,722,915

incentives to transition marginal land used for annual crop production in the previous two years or greater (Government of Saskatchewan, 2023b). Compensation for implementing this transition include 50 % coverage of establishment costs, including seed and seeding, accompanied by an annual C$20/acre payment for maintaining the perennial forage stand for the following 5 years (Government of Saskatchewan, 2023b). This translates to an annual payment of C$49.42/ha throughout the duration of the stand. Compensation for establishment and seed totals C$60/acre, or $148.26/ha. The entirety of the C$197.68 payment is made upon project completion when accompanied by the signing of a land use agreement. Considering the future value this payment throughout the five-year period at six-percent cost of capital provides an average annual payment of C$52.91/ha. This falls within the range of values identified by the current research; however, the value issued through the Resilient Agricultural Landscapes Program (RALP) does not match values indicated by the SCC and Canadian Carbon Tax. Additionally, funding amounts for these programs are often based on economic analyses considering producer willingness to pay (e.g., Ingram et al., 2023) and do not account for the direct value of ecosystem services provided. In future iterations of the SCAP program, values could be re-evaluated to consider the value of SOC accumulation.

A multitude of conservation policy frameworks are available to producers under the current iteration of the SCAP (Government of Saskatchewan, 2023b). The programs provide cost-sharing programs to implement BMPs on both native and seeded grasslands. However, conservation easements serve as another potential avenue to advocate proper grassland management. Until recently, the availability of easements to Saskatchewan ranchers operated in perpetuity, controlling land use and devaluing land indefinitely (Ndolo, 2018). The strict stipulations surrounding land use in easements has made the conservation alternative unpopular amongst Saskatchewan cow-calf producers (Ingram et al., 2023).

Recent restructuring of funding agreements between producer organizations and government bodies have made term easements accessible to producers.[10] Operating on 30-year terms, these term agreements offer approximately 37.5 % of land market value in exchange for not breaking, developing, or draining grasslands. In 2023, the average value of Saskatchewan forage lands was determined to be C $933/acre by Farm Credit Canada (2024), translating to C$2305 per ha. Based on this value a term easement would pay approximately C$864/ha; annualizing this result at a 4 % cost of capital yields a payment of C $93.41/ha. This value also falls within the range of values estimated by the present research with the closest alignment in value being the Canadian Carbon Tax.

Based upon the findings a similar program pertaining to seeded perennial forage stands would provide value to cow-calf producers while enhancing climate change mitigation efforts. The structuring of such agreements would be more complex given the desire to rejuvenate perennial forage stands after 5–10 years according to the results presented above. As such, agreements stipulating the use of seeded perennial forage stands could make allowances for this by adapting term length or stipulating acceptable rejuvenation practices aiming to avoid the breaking of forage stands.

5. Conclusions

Considering the important linkage between fertilization and the net emissions of forage production the adoption of beneficial fertilizer technologies is warranted. However, before large scale changes can occur research studying the impact of novel fertilizer technologies in a forage context must be completed. This will require the provision of funds from public sources to research entities best equipped to study these impacts. Other crop production-based studies (e.g., Fast et al., 2023; Owens et al., 2023) analyze the impacts of enhancements in fertilizer technologies in a Western Canadian context. Further analysis quantifying the productivity and environmental impacts of novel fertilizer technologies on forage crops is warranted.

The present work has provided substantive evidence that forage production provides a sustainable alternative to crop production, especially on marginal lands. However, several limitations must be noted. First, the study was based in the province of Saskatchewan and cannot adequately advise policies surrounding forage production at the national level. Secondly, the small sample size relative to the total number of ranchers in the study area necessitates results be interpreted with caution despite clear linkages between the demographics of respondents and that of all Saskatchewan cow-calf producers. Thirdly, the size of farms in the Forage Production Survey was larger than census data and may not adequately represent small scale production. Finally, the present work is believed to provide conservative estimates relative to the total C sequestration potential of Saskatchewan forage lands. The exclusion of native grasslands and wetlands from the present study limits the ability to capture the entirety of preserved forage production in Saskatchewan. Canadian emission accounting frameworks could be better adapted to include lands of this type.

CRediT authorship contribution statement

Judson Christopherson: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Stuart J. Smyth:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare no conflict of interest.

Data availability

The authors do not have permission to share data.

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