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Synthesis

Land Management History of Canadian Grasslands and the Impact on Soil Carbon Storage

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Abstract

Grasslands represent a large potential reservoir in storing carbon (C) in plant biomass and soil organic matter via C sequestration, but the potential greatly depends on how grasslands are managed, especially for livestock and wild animal grazing. Positive and negative grazing effects on soil organic carbon have been reported by various studies globally, but it is not known if Canadian grasslands function as a source or a sink for atmospheric C under current management practices. This article examines the effect of grassland management on carbon storage by compiling historical range management facts and measurements from multiple experiments. Results indicate that grazing on grasslands has contributed to a net C sink in the top 15-cm depth under current utilization regimes with a removal rate of CO_2 at $0.19 \pm 0.02\ \mathrm{Mg \cdot C \cdot ha^{-1} \cdot yr^{-1}}$ from the atmosphere during recent decades, and net C sequestration was estimated at $5.64 \pm 0.97\ \mathrm{Mg \cdot C \cdot ha^{-1}}$ on average. Naturalization of 2.3 M ha of previously cultivated grasslands in the 1930s has also led to C sequestration in the Canadian prairies but has likely abated as the pool has saturated. Efforts made by researchers, policymakers, and the public has successfully led to the restoration of the Canadian prairies to a healthier state and to achieve considerable C sequestration in soils since their severe deterioration in the 1930s. In-depth analysis of management, legislation, and agricultural programs is urgently needed to place the focus on maintaining range health and achieving more C storage in soils, particularly when facing the reduced potential for further C sequestration.

Key Words: Canadian grazing grasslands, cultivation abandonment, grassland carbon restoration, grassland deterioration, naturalized grasslands, soil carbon sequestration

INTRODUCTION

Carbon dioxide concentration in the atmosphere has increased by 100 $\mu\mathrm{mol \cdot mol^{-1}}$ during the last 150 yr (Morgan et al. 2004), which has contributed to climate change in the last century (Woodwell et al. 1995). Natural and managed ecosystems, however, offer opportunities to mitigate CO_2 release due to the vast potential of C storage in soil given their large geographic distribution (Bagchi and Ritchie 2010). It has been estimated that adopting improved land management practices has the potential to offset up to one-third of global greenhouse gas emissions annually (Lal 2004). Carbon sequestration can also provide a positive feedback to the ecosystem through improved soil quality and reduced soil erosion (Derner and Schuman 2007).

Grasslands represent the largest land resource in the world, occupying 40% of the earth's land surface (Wang and Fang 2009) and storing over 10% of terrestrial biomass C and nearly 30% of the global soil organic carbon (SOC) stock (Scurlock and Hall 1998). Many grassland areas have suffered losses of SOC over recent decades due to intensive grazing and agricultural use and thus may have a large potential to sequester lost C back into the soil (Reid et al. 2004). Schlesinger (1997) reported that grasslands globally sequester C in soil at a rate of $0.5\ \mathrm{Pg \cdot C \cdot yr^{-1}}$. Although the rate is far lower than in improved croplands and pastures, the contribution of grasslands in terrestrial C storing accounts for a significant C sequestration given the large area of land resources and minimal requirement of inputs (Derner and Schuman 2007). Grasslands C sequestration can be influenced by many factors, such as biome composition, climate change (Conant et al. 2001), and management practices (Jones and Donnelly 2004). Grazing has been treated as a major influence on grassland C sequestration due to the expansive use of this practice and the large potential to store SOC globally (Olff et al. 2002).

Originally, the natural grasslands of Canada covered about 61 500 000 ha, which extended across broad areas of Alberta, Saskatchewan, and southern Manitoba (Clayton et al. 1977). At present, residual grasslands occupy only less than 11 000 000 ha, and their distribution is highly geographically fragmented (Statistics Canada 1991–2011). Fifty million hectares of the original natural grassland have been cultivated with wheat and other crop production and urban expansion. The primary use of the remaining natural grasslands is for the grazing of domestic livestock and wildlife. Other natural grasslands are conserved by the Crown and through pasture maintenance, national parks, and military installations, which are estimated to represent 1 540 000 ha in total (McCartney and Horton 1999).

The initial cultivation of grasslands resulted in large losses of SOC. Studies have reported that between 20% and 60% of

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carbon stored in surface soils was lost during the conversion to croplands (Bowman et al. 1990; VandenBygaart et al. 2003). Nonetheless, C can be restored by applying improved practices, such as reduced tillage, improved crop nutrition, applying organic amendments, or reverting to perennial vegetation (Janzen et al. 1998). For example, SOC content increased by about 4 $Mg \cdot C \cdot ha^{-1}$ after adopting no-tillage for 11 yr in southern Saskatchewan (Janzen et al. 1998). Application of 75 $Mg \cdot ha^{-1}$ manure resulted in a 12 $Mg \cdot C \cdot ha^{-1}$ increase in SOC compared to unamended treatments in central Alberta (Izaurralde et al. 1997). Grazing affects grassland carbon storage in a very complex manner (Pineiro et al. 2010). The loss of SOC has been attributed to lowered primary production and increased soil erosion from reduced ground cover under overgrazing and poor management (Su et al. 2005). Increases and no change in SOC are believed to occur as grazing reduces the standing dead and surface litters, while traffic enhances physical breakdown and incorporation of residual plant material into surface soil (Manley et al. 1995). It has been estimated that several percent (Henderson 2000, 2004) to 40% (Willms et al. 2002) of the C stored in surface soil can be lost due to overgrazing compared to never-grazed native areas across different Canadian natural grasslands, while Naeth et al. (1991) reported that SOC storage increased by 2–19 $Mg \cdot ha^{-1}$ on Canadian fescue grassland compared to ungrazed areas after 46 yr of light and heavy grazing management. No change has been documented by Li et al. (2012) that grassland soil organic C stocks remained unchanged after the long-term grazing of cattle for 58 yr in Alberta, Canada.

In this study, we provide a review of the current knowledge on the effect of management practices on C sequestration in Canadian rangelands by compiling historical facts and actual measurements from individual experiments. We explored whether the Canadian grasslands act as a C sink under current management practices. The development of the Canadian grasslands is assessed from prehistory to the present, including major disturbances by land management.

GRASSLAND IN PREHISTORY

The ancient grasslands of the Canadian prairies have adapted to climate, natural fires, and grazing animals for about 55 000 000–100 000 000 yr as the Rocky Mountains were orographically uplifted. The chain of mountains modified the hydrologic system from a Pacific influence to one with a drier continental climate. This caused vegetation shifts from moisture-loving Actoteriary flora to more drought-tolerate grasslands, shrublands, and deciduous forests (Bailey et al. 2010). The ancient Canadian prairies stretch about 1 800 km from southeastern Manitoba to northwestern Alberta, and all uplands and riparian areas were habitats for wild ungulates, predators, small mammals, reptiles, amphibians, songbirds, insects, and arthropods (Bailey et al. 2006). During the Pleistocene epoch, grasslands were grazed by horses, wild camels, and other mammals and were replaced by bison approximately 10 000 yr ago (Dyck 1983). Aboriginals appeared on the North America continent during the last ice age 40 000 yr ago by crossing the Bering Strait land bridge from Asia to Alaska, and they first immigrated to the Canadian prairies at least 16 000 yr ago (Goebel et al. 2008).

Carbon storage in Canadian grassland soils has evolved with changing patterns of animal grazing, vegetation shifts, climate fluctuations, and fires for millions of years. Although the exact trends of C change in soils cannot be known, the compiled effect of climate and animal grazing during this period is expected to have contributed largely to C accumulation (Table 1). Soils of the western Canadian prairies are considered young but very fertile, accumulating high levels of organic matter in the Ah horizon after ice melt 12 000–15 000 yr ago (Bailey et al. 2006). Three main soils are classified on the Canadian prairie: the Brown soil zone dominates the driest part of southern Alberta and adjacent Saskatchewan of the Dry Mixed Grass ecoregion, the Dark Brown soil zone occupies a somewhat moister area of Mixed Prairie ecoregion, and the Black soil zone is dominated by black Chernozems and Solonetzic soils in comparatively moister areas of the Foothill and Parkland Fescue ecoregion.

GRASSLAND MANAGEMENT DURING EARLY SETTLEMENT AND SOC IMPLICATIONS

Politics of Western Settlements

Around 1600, Europeans appeared on the prairie, an event instigated by exploring the new potential of beaver fur trades (Willms et al. 2011). Later, the competition between the Hudson's Bay Company (formed by British settlers in 1670) and the North West Company (formed by French traders from Montreal in 1783) for the fur business, as well the desire to bring authority to the interior lands, yielded several other waves of western settlements (Martin 1920). The biggest influence of European settlers to the prairie areas was the deracinate fate brought to both the aboriginals and the bison they relied on. Bison were slaughtered to near extinction by 1879. The building of the Canadian Pacific Railway (CPR) from 1881 to 1885 provided the key for westward transportation. The Dominion Lands Act (also named the Homesteader Act) created by the Department of Interior in 1872 opened natural "cultivable" grassland to homesteaders that greatly promoted a settlers rush to "The Last Best West" (Martin 1938). Lands were surveyed and subdivided. The Department of Interior granted settlers with a $10 registration fee, but they had to abide to strict requirements: a quarter section of 160 acres (64 ha) had to be cultivated before receiving a title to the lands. In addition, the construction of the CPR provided business opportunities for immigrants. Packages that included passages on a Canadian Pacific ship, overland travel by CPR, and the land was sold for only $2.50 per acre. The immigration policy of the government was a huge success at that time. Before 1870, only fewer than 1 000 nonaboriginal people resided on the Canadian prairie areas. In Alberta alone, the population increased from about 73 000 in 1901 to about 375 000 in 1911. In Saskatchewan, the population also reached nearly 500 000 in 1911 (Willms et al. 2011).

Farm Practices and Range Management

The attitude of European settlers toward the native land and vegetation was influenced largely by Roman cultures that

Table 1. Summary of time line, events, and estimation of carbon state and change on natural grasslands of the Canadian Prairies.

Stages	Time line	Event	Carbon state and trend	Summary
Prehistory	80 000 000–50 000 000 yr	Rocky Mountains aroused by Laramie Orogeny	Grasslands evolved and adapted to natural fire, grazing, and climate highly self-adjusted carbon storage	Formed carbon baseline
		Canadian grasslands initially formed by climate shifts		
	2.58 000 000–10 000 yr	The current ice age started		
		Ice sheet prevented and retreated repeatedly		
	50 million–10 000 yr	Ancient animals appeared on grasslands		
		Wild camels and horses were domain grazing animals		
	Approx. 40 000 yr	Aboriginals first immigrated to North America		
	Approx. 16 000 yr	Aboriginals first immigrated to Canadian prairies		
Bison stage	10 000 yr	Bison appeared on Canadian grassland as dominant grazers	Carbon change affected by bison grazing but assumed under self-adjusted equilibrium	No change
	Around 1790	Bison expanded to 60 000 000 head on Canadian grasslands		
Cattle stage	1791–1879	Bison decimated due to drought and slaughter		
Naive ranch time	1813	The first cattle brought to the Canadian grassland	Carbon loss in some areas due to overgrazing, but in general carbon not changing on large scale because of the relatively small cattle number, inputs, and increased ANPP due to the release from bison grazing pressures and agreeable climate	No change
	1860s	Livestock began to expand in eastern grasslands in Manitoba		
	1870s	Cattle arrived in Alberta and Saskatchewan and started to expand		
	1881	9 000 head on Canadian prairie, stocking rate at 10 acre · $head^{-1}$		
	1890s	50 000 head on Canadian Prairie, stocking rate at 8–12 ha · AU^{-1}		
	1901–1906	Golden age of ranching, cattle numbers increased rapidly		
	From 1907	Severe winters of 1886–1887, 1906–1907, 80% of cattle eliminated		
	1911–1940s	Cattle number boosted greatly on western grasslands	Carbon loss due to overgrazing and severe drought	C loss
		High stocking rate; overgrazing widespread		
	1917–1938	Drought affected entire western Canadian grassland areas		
Grassland conversion	1850	European settlers initially investigate the west for the fur trade	Carbon decreased significantly by 40–60% by cultivation; large C loss in 1930s due to severe drought and inexperienced land management	C loss
	1881–1885	Building of CPR was the key of immigration to western prairie areas		
	1896–1906	First rapid of transition to the west		
	1906–1916	Another big transition on the rest of grassland areas.		
	1881–1930s	Large area of natural grassland cultivated for various crops until drought occurred in 1930s		
	1930–1938	7 000 farmers abandoned their farmlands		
		Abandoned area provided a stimulus of seeding perennial forages		
		Stimulated Prairie Farm Rehabilitation Administration established in 1935		
Grass reseeded	Since 1930	Crested wheatgrass seeded to 77 000 ha by 1954 and seeded to 1 000 000 ha by 1980s	Carbon restored on reseeded areas	C restored
	Early 1950s	Russian wild rye was recognized as a potential pasture grass		
		100 000 ha were seeded by the late 1970s		
		Abandoned area provided time for grassland restored naturally	Carbon restored on abandoned areas	C restored
	From 1980s	Conversions from various croplands to permanent grasses	Carbon restored on converted area	C restored
Prudent ranch time	1961	Feedlot appeared in Canada, lowering down grazing pressures	No loss of SOC under current grazing regimes on natural grasslands	C sequestered
	1950s to present	Improved grassland grazing management		
		Lowered stocking rate		
Improved farming	Since 1930s drought	Various improved managements on cultivated farmlands	C gained due to advanced farming practices	C gained but still lower than native

[1]SOC indicates soil organic carbon.

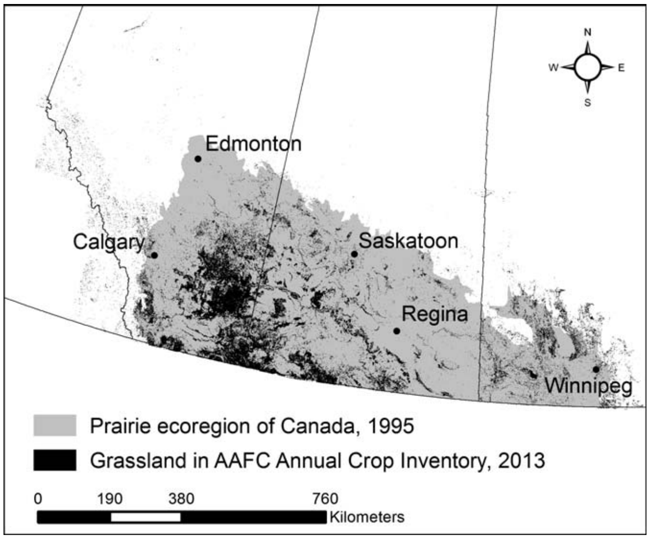

Figure 1. Original and remaining areas of prairie grasslands of Canada. AAFC indicates Agricultural and Agri-Food Canada.

considered all natural lands as unattractive and worthless and as such must be cultivated (Bailey et al. 2010). Huge native areas were put into production (Fig. 1). Only 870 ha of grassland were cultivated by 1831, but this sharply increased to 113 000 ha in 1881, and by 1931 about 24 000 000 ha of the natural grasslands were cultivated and converted to croplands. Until 1991, about 38 450 000 ha of natural grasslands were cultivated (Statistics Canada 1991–2011). Tamed and seeded pastures also increased from 312 500 to 3 159 000 ha from 1921 to 1991 (Table 2). The "must be cultivated" attitude of settlers could also be recognized by its designation employed by Statistics Canada. Initially (around 1900), Statistics Canada classified cultivated land as "improved land," while "unimproved land" referred to natural grasslands with no cultivation. Similarly, terminologies of "improved pastures" and "unimproved pastures" were applied to separate grassland cultivated and seeded to forage grasses with the purpose of increasing production and the natural grasslands. This designation persisted until the 1991 census, after which the terms were revised to "tamed or seeded pasture" and "natural land for pasture" or "native land for grazing" (Statistics Canada 1991–2011).

After the bison extirpation around 1880, livestock became the dominant grazer of the Canadian grasslands. In 1881, there were about 9 000 head of cattle in the northwest, but by the 1890s this number increased sharply to 50 000, corresponding with the establishment of the CPR (Anderson 1988). From 1901 to 1906, cattle populations exploded from 212 145 to 360 236 in Saskatchewan alone (Anderson 1988). During this stage, cattle ranching was a typical low-input extensive operation with a heavy focus on grazing (Johnston 1970). Stocking rate changed from 4 $ha \cdot AU^{-1}$ in 1881 to 8 $ha \cdot AU^{-1}$ in 1888 and then to 12 $ha \cdot AU^{-1}$ in 1930 (Fig. 2) but still greatly exceeded the recommended stocking rate for mixed prairie in Alberta today at 24–40 $ha \cdot AU^{-1}$ to maintain grassland health (Adams et al. 2005). In addition, ranchers considered storing hay for livestock in winter unnecessary. But during the extreme winters of 1886–1887 and 1906–1907, over

Table 2. Natural grazing grassland area and pasture area of three prairie provinces in Canada, 1921–2011.

	Natural land for pasture				Tamed and seeded pasture			
	AB[1]	SK	MB	Total	AB	SK	MB	Total
	ha							
Year[2]								
1921	5 547 897	6 067 539	1 613 757	13 229 193	56 514	87 151	168 887	312 552
1931	6 489 478	6 375 900	1 494 626	14 360 005	202 059	288 287	166 700	657 045
1941	7 466 502	8 147 528	1 952 009	17 566 040	246 181	319 821	184 329	750 331
1951	—[3]	—	—	—	390 021	583 159	236 629	1 209 808
1961	7 005 206	6 413 085	1 289 578	14 707 869	675 984	564 216	291 301	1 531 501
1981	—	—	—	—	1 581 439	975 359	352 510	2 909 308
1986	—	—	—	—	1 376 809	878 729	274 940	2 530 478
1991	6 674 107	5 397 719	1 750 507	13 822 333	1 742 479	1 075 659	341 290	3 159 428
1996	6 615 421	5 093 514	1 653 665	13 362 600	1 914 599	1 233 309	356 240	3 504 148
2001	6 678 905	5 126 747	1 580 375	13 386 027	2 230 894	1 405 736	383 474	4 020 104
2006	6 529 870	5 175 795	1 548 199	13 253 863	2 483 704	1 962 224	498 295	4 944 224
2011	6 435 832	4 816 787	1 466 969	12 719 588	2 395 946	2 057 959	415 323	4 869 228
Change (rate)								
1921–2011	0.16	−0.21	−0.09	−0.04	41	23	15	15
1991–2011	−0.04	−0.11	−0.16	−0.08	0.38	0.91	0.22	0.54

[1]AB, SK, and MB indicate Alberta, Saskatchewan, and Manitoba, Canada, respectively.

[2]The recorded name of this area from 1921 to 1951 was "Prairie or Natural Pasture—unimproved." The name of 1961 was changed to "Area of unimproved land used for pasture." Data from 1991 to 2011 were received from the Census of Agriculture (Statistic Canada), which was recorded in every 5 yr with the name of "Natural land for pasture." Data for tamed and seeded pasture were received from the same data source as natural land for pasture. The name used from 1921 to 1961 was "Pasture" and was changed to "Improved land for pasture or grazing" in 1961. The name used from 1981 to 2011 was "Tamed or seeded pasture."

[3] — indicates data not available.

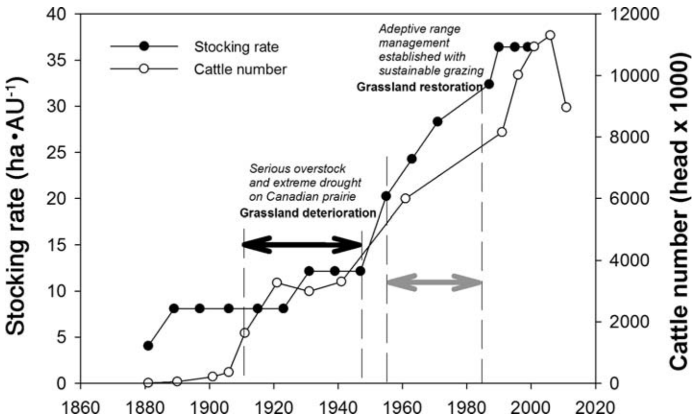

Figure 2. Cattle number and recommended stocking rates on Canadian grazing grasslands from 1860 to present. Actual stocking rates from 1955 to the present were summarized from six large grazing leases in southern Alberta (Adams et al. 2004). Feedlot appearance after 1961 largely reduced grazing pressure on grasslands.

80% of the cattle died due to either starvation or freezing (Willms et al. 2011). The huge loss initiated ranchers to begin storing hay for cattle, resulting in another boom for the cattle industry after 1910. From 1911 to 1941, cattle numbers exploded from 746 576, 449 264, and 435 538 head to 1 353 141, 1 241 145, and 705 337 head in Alberta, Saskatchewan, and Manitoba provinces, respectively (Willms et al. 2011). This resulted in vast areas of the Canadian prairie being overgrazed, having a large effect on the C dynamics (Table 1).

C Change

Before 1880, Canadian grasslands were grazed primarily by bison. Bison population had once boomed to 60 000 000 head around 1790 before their extirpation (Hamalainen 2003). The grassland ecosystem during the "bison stage" was likely under a grazer-induced equilibrium (Table 1). Overgrazing sometimes occurred close to water resources. But when drought arrived, fires removed forages, and a large number of grazers died from starvation, lack of water, or disease (Bailey et al. 2010). The reduced number of grazers provided the opportunity for grasslands to be restored to a healthier state, and this would be reflected in the SOC status. Bison would have heavily grazed and trampled some grassland areas when herds were large. This may have led to a SOC reduction in some areas in a short time period due to the reduction in net primary production. But bison usually would not tend to return to the same location that year or perhaps for several years, assuring that the grasslands recovered to a healthier state (Willms et al. 2011). Therefore, we assumed the carbon storage of Canadian grasslands during the bison stage was highly self-adjusted. C loss may be predicted in some areas in certain years when drought occurred within areas of overgrazing. But generally, carbon storage in soils would likely have remained in an equilibrium state during the entire bison stage in all grassland distributions.

Both livestock ranching and cultivation on Canadian grasslands were initiated at the end of the bison stage (Table 1). Although SOC storage would have been reflected by the intensive management on both native and cultivated lands, it was reduced to a historically low status when drought was extensive from the 1910s to 1930s. From the 1880s to the 1910s, SOC storage was likely at equilibrium on grazed lands since cattle numbers were not large. Also, SOC in some areas might have been lowered due to overgrazing, but on a large geographical scale, this C loss would have been compensated by the increased primary production during the vigorous regrowth after recovery from bison overgrazing and the agreeable climate condition during this time frame. SOC storage in some areas might have even increased during the first several years because of the increased plant growth through enhanced manure nutrient inputs from livestock (Milchunas and Lauenroth 1993). From 1910 to 1930, however, soil C of Canadian grazing grassland was assumed to be considerably reduced due to a sharp increase in cattle numbers (Fig. 2), high grazing pressure, and extremely dry climate (Schuman et al. 2005).

Due to a large area of cultivated grasslands, large amounts of SOC were lost to oxidation and possibly wind erosion from the 1880s to the 1930s. SOC losses were likely even greater during the period of 1910–1930 because of the poor management practices employed by inexperienced land managers (e.g., deep plowing) as well as the extremely dry climate (Table 1). Lacking consideration of land utilization and drought, this eventually brought enormous ecological disaster and social disruption to the Canadian prairies. During the 12-yr drought from 1917 to 1930, topsoil was eroded by wind, soil salination occurred, soil organic matter declined, and nutrients were lost across much of the Canadian grassland areas (Bailey et al. 2010).

CURRENT GRASSLAND MANAGEMENT AND C SEQUESTRAION

Natural Grassland for Grazing

The Depression and the Dust Bowl periods were the precursors to the realization that grasslands were vulnerable landscapes and that improper management could be catastrophic. Roberts et al. (2006) estimated that drought can occur once every 3 yr on the Canadian prairie, and nearly 40 droughts were recorded in the past 100 yr. Generally, absence of grazing is not recommended on natural grasslands because the ecosystems have evolved with grass species that require regular grazing for optimal health. Ranchers and livestock farmers have learned that factors such as stocking rate, season of grazing, adequate animal distribution, and drought are critical to the optimum management of the grasslands. Policy changes of cattle grazing reflect this shift in which stocking rate was lowered greatly from 20 $ha \cdot AU^{-1}$ in 1955 to 36 to 40 $ha \cdot AU^{-1}$ at present in southern Alberta (Fig. 2). The reduced grazing pressure allowed for grasslands to recover back to a healthy condition after their severe deterioration. Other improved management practices were applied by livestock managers. Annual forages, forested rangelands, annual crop windrows, and intensive managed pastures were all effective as complementary practices to grazing on the grasslands systems in Canada, allowing cattle numbers to continue to increase while stocking rate on the grasslands declined (Fig. 2).

Table 3. Grazing effects on soil organic carbon in Ah horizons of Canadian grazing grasslands.

Author	Location	MAP[1]	Soil[2]	Vegetation[3]	Initiate	End	Length	Intensity[4]	Net C change[5]	C change rate	Mean ± SE	Mean ± SE
									($Mg \cdot ha^{-1}$)	($Mg \cdot ha^{-1} \cdot yr^{-1}$)	—	—
Li et al. (2012)	Stavely, AB[6]	502	B	F	1949	2007	58	H	−1.00	−0.02	—	—
	Stavely, AB	502	B	F	1949	2007	58	M	−0.90	−0.02	—	—
Henderson et al. (2004)	South AB	384	NA	NA	1927–1979	1999	42	M	−2.18	−0.05	—	—
Henderson (2000)	Picture Butte, AB	374	DBR	M	1978	1999	21	H	5.38	0.26	—	—
	Turin, AB	360	DBR	M	1976	1999	23	H	1.50	0.07	—	—
	Onefour A, AB	351	BR	DM	1948	1999	51	L	0.31	0.01	—	—
	Onefour B, AB	351	BR	DM	1927	1999	72	L	0.52	0.01	—	—
	Onefour C, AB	351	BR	DM	1927	1999	72	L	5.28	0.07	—	—
	Stavely B, AB	476	B	F	1949	1999	50	L	5.32	0.11	—	—
	Stavely C, AB	476	B	F	1949	1999	50	L	2.96	0.06	—	—
	Hays, AB	328	BR	DM	1979	1999	20	M	1.83	0.09	—	—
	Twin river, AB	390	DBR	F	1970	1999	29	M	3.82	0.13	—	—
Dormaar and Willms (1998)	Southwest, AB	550	B	F	1949	1992	43	H	5.73	0.13	—	—
	Southwest, AB	550	B	F	1949	1992	43	L	11.56	0.27	—	—
	Southwest, AB	550	B	F	1949	1992	43	VH	1.95	0.05	—	—
Dormaar et al. (1997)	Brooks, AB	355	BR	M	1982	1987	5	H	−0.97	−0.19	—	—
	Brooks, AB	355	BR	M	1987	1992	5	M	6.00	1.20	—	—
Dormaar et al. (1994)	Lethbridge, AB	425	DBR	M	1931	1991	60	M	2.93	0.05	—	—
	Lethbridge, AB	425	DBR	M	1931	1991	60	M	6.62	0.11	—	—
Dormaar and Willms (1992)	Stavely, AB	500	B	F	1949	1988	39	L	17.48	0.45	—	—
	Stavely, AB	500	B	F	1949	1988	39	L	18.25	0.47	—	—
	Stavely, AB	500	B	F	1949	1988	39	L	21.38	0.55	—	—
	Stavely, AB	500	B	F	1949	1988	39	L	21.58	0.55	—	—
	Stavely, AB	500	B	F	1949	1988	39	L	18.92	0.49	—	—
	Stavely, AB	500	B	F	1949	1988	39	L	18.38	0.47	—	—
	Stavely, AB	500	B	F	1949	1988	39	VH	15.42	0.40	—	—
	Stavely, AB	500	B	F	1949	1988	39	VH	16.81	0.43	—	—
	Stavely, AB	500	B	F	1949	1988	39	VH	21.73	0.56	—	—
	Stavely, AB	500	B	F	1949	1988	39	VH	22.12	0.57	—	—
	Stavely, AB	500	B	F	1949	1988	39	VH	18.48	0.47	—	—
	Stavely, AB	500	B	F	1949	1988	39	VH	17.78	0.46	—	—
Naeth et al. (1991)	Stavely, AB	550	B	F	1949	1985	36	H	−4.00	−0.11	—	—
	Kinsella, AB	422	B	F	1973	1985	12	H	5.00	0.42	—	—
	Kinsella, AB	422	B	F	1973	1985	12	H	19.00	1.58	—	—
	Stavely, AB	550	B	F	1949	1985	36	L	−11.00	−0.31	—	—
	Kinsella, AB	422	B	F	1973	1985	12	L	4.00	0.33	—	—
	Kinsella, AB	422	B	F	1973	1985	12	L	2.00	0.17	—	—
	Stavely, AB	550	B	F	1949	1985	36	M	−11.00	−0.31	—	—
	Brooks, AB	355	BR	M	1964	1985	21	M	−1.00	−0.05	—	—
	Brooks, AB	355	BR	M	1964	1985	21	M	5.00	0.24	—	—
	Stavely, AB	550	B	F	1949	1985	36	VH	−10.00	−0.28	—	—
Dormaar et al. (1990)	Stavely, AB	500	B	F	1949	1967	18	L	−11.82	−0.66	—	—
	Stavely, AB	500	B	F	1949	1986	37	L	6.24	0.17	—	—
	Stavely, AB	500	B	F	1949	1967	18	VH	−0.21	−0.01	—	—
	Stavely, AB	500	B	F	1949	1986	37	VH	−7.63	−0.21	—	—
Willms et al. (1990)	Taber, AB	382	BR	M	1979	1987	8	L	−2.57	−0.32	—	—
Dormaar et al. (1989)	Fort Macleod, AB	450	B	F	1981	1985	4	H	−4.58	−1.14	—	—
	Fort Macleod, AB	450	B	F	1981	1986	5	H	−1.74	−0.35	—	—
	Fort Macleod, AB	450	B	F	1981	1986	5	H	−2.12	−0.42	—	—
	Fort Macleod, AB	450	B	F	1981	1985	4	H	0.55	0.14	—	—

Table 3. Continued.

Author	Location	MAP[1]	Soil[2]	Vegetation[3]	Initiate	End	Length	Intensity[4]	Net C change[5]	C change rate	Mean ± SE	Mean ± SE
Willms (1988)	Stavely, AB	348	B	F	1949	1987	38	H	3.76	0.10	—	—
	Stavely, AB	348	B	F	1949	1987	38	H	2.01	0.05	—	—
	Stavely, AB	348	B	F	1949	1987	38	L	4.98	0.13	—	—
Dormaar et al. (1984)	Stavely, AB	500	B	F	1951	1978	27	H	6.52	0.24	—	—
	Stavely, AB	500	B	F	1951	1979	28	H	7.77	0.28	—	—
	Stavely, AB	500	B	F	1951	1980	29	H	11.07	0.38	—	—
	Manyberris, AB	310	BR	M	1951	1979	28	H	3.69	0.13	—	—
	Manyberris, AB	310	BR	M	1951	1978	27	H	7.00	0.26	—	—
Dormaar et al. (1977)	Stavely, AB	500	B	F	1951	1973	22	H	10.19	0.46	—	—
	Stavely, AB	500	B	F	1951	1973	22	H	10.84	0.49	—	—
	Stavely, AB	500	B	F	1951	1973	22	H	10.32	0.47	—	—
	Stavely, AB	500	B	F	1951	1973	22	H	11.22	0.51	—	—
	Manyberris, AB	310	BR	M	1951	1973	22	H	3.32	0.15	—	—
	Manyberris, AB	310	BR	M	1951	1973	22	H	2.84	0.13	—	—
	Manyberris, AB	310	BR	M	1951	1973	22	H	6.25	0.28	—	—
Smoliak et al. (1972)	Manyberris, AB	310	BR	M	1951	1970	19	H	5.54	0.29	—	—
	Manyberris, AB	310	BR	M	1951	1970	19	L	0.61	0.03	—	—
	Manyberris, AB	310	BR	M	1951	1970	19	M	1.32	0.07	—	—
Johnston et al. (1971)	Stavely, AB	502	B	F	1951	1967	16	H	9.22	0.58	—	—
	Stavely, AB	502	B	F	1951	1967	16	L	12.27	0.77	—	—
	Stavely, AB	502	B	F	1951	1967	16	M	10.81	0.68	—	—
	Stavely, AB	502	B	F	1951	1967	16	VH	5.41	0.34	—	—
Data summary												
Overall	—	—	—	—	—	—	—	—	—	—	5.64 ± 0.97	0.19 ± 0.02
Soil type	—	—	B	—	—	—	—	—	—	—	7.00 ± 1.36	0.22 ± 0.06
	—	—	BR	—	—	—	—	—	—	—	2.65 ± 0.71	0.14 ± 0.07
	—	—	DBR	—	—	—	—	—	—	—	4.05 ± 0.90	0.12 ± 0.04
Vegetation	—	—	—	DM	—	—	—	—	—	—	1.99 ± 0.99	0.04 ± 0.02
	—	—	—	F	—	—	—	—	—	—	6.94 ± 1.33	0.22 ± 0.06
	—	—	—	M	—	—	—	—	—	—	3.14 ± 0.74	0.16 ± 0.08
Intensity	—	—	—	—	—	—	—	L	—	—	6.98 ± 2.15	0.18 ± 0.07
	—	—	—	—	—	—	—	M	—	—	2.31 ± 1.69	0.20 ± 0.12
	—	—	—	—	—	—	—	H	—	—	4.80 ± 1.04	0.18 ± 0.09
	—	—	—	—	—	—	—	VH	—	—	9.26 ± 3.55	0.25 ± 0.09

[1]MAP indicates mean annual precipitation for a given site.
[2]B, BR, and DBR indicate black soil, brown soil, and dark brown soil, respectively.
[3]F, DM, and M indicate fescue, dry mixed, and mixed grasses association, respectively.
[4]H, L, M, and VH indicate heavy, light, moderate, and very heavy grazing intensity, respectively.
[5]SOC stock values are reported in units of SOC concentration, and SOM concentrations are calculated by times C concentration, bulk density, and thickness of a given depth together using equations from Ellert and Bettany (1995). SOC%=0.58×SOM% (Mann 1986).
[6]AB indicates Alberta, Canada.

Have these improved grazing management practices induced C to be stored in Canadian grazing grasslands? To answer this question, we summarized the studies recording grassland SOC that compared a grazed sample plot to a control plot initiated in Canada under varying environments and experimental designs (Table 3). The experimental length of the studies covered a time frame of 80 yr from 1927 to 2007. Most studies were initiated after 1949 following deterioration and implementation of adaptive management with sustainable grazing stocking rates applied. Another three studies spanned a time frame of 1927–1931 to 1991–1999, also occurring mostly in the period of grassland restoration under prudent management. Most observations we selected were reporting SOC change in the Ah horizon; therefore, we focus only on discussing the carbon change in the Ah horizon of Canadian grassland soils. Table 3 shows a general net carbon gain on Canadian grazed grasslands in recent decades. The amount of carbon sequestration was estimated to be 5.64 $Mg \cdot ha^{-1}$ on average, and the sequestration rate was estimated to be 0.19 $Mg \cdot ha^{-1} \cdot yr^{-1}$. Net carbon sequestration for the three main prairie soil types were 7.00, 2.65, and 3.01 $Mg \cdot ha^{-1}$ for Black, Brown and Dark brown soil, yielding rates of change of 0.22, 0.14, and 0.09 $Mg \cdot ha^{-1} \cdot yr^{-1}$, respectively. Net carbon sequestration for the three main prairie grass associations were estimated to be 1.99,

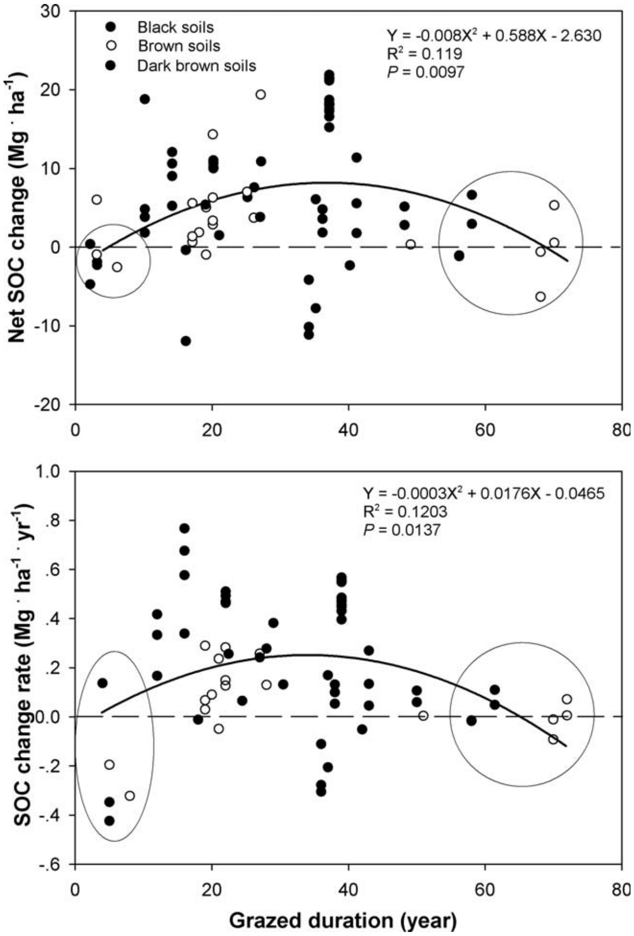

Figure 3. Net soil organic carbon (SOC) change and SOC change rate for the Ah horizon with respect to time grazed.

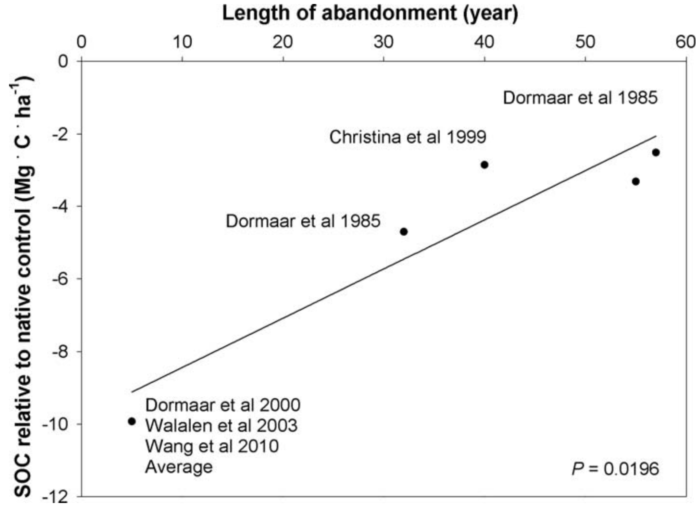

Figure 4. Soil organic carbon (SOC) compared to native control as a function of restoration length on Canadian abandoned lands.

6.94, and 3.14 $Mg \cdot ha^{-1}$ for dry mixed, fescue, and mixed grasses, yielding rates of C change of 0.05, 0.22, and 0.16 $Mg \cdot ha^{-1} \cdot yr^{-1}$, respectively. Grazing intensity had little impact on soil carbon storage with soil carbon increasing under both light and heavy grazing. Net C sequestration was estimated to be 6.98, 2.31, 4.80, and 9.26 $Mg \cdot ha^{-1}$ for light, moderate, heavy, and very heavy intensity, yielding rates of C change of 0.18, 0.20, 0.18, and 0.25 $Mg \cdot ha^{-1} \cdot yr^{-1}$, respectively. All C sequestration rates agreed with the range of 0.07–0.30 $Mg \cdot ha^{-1} \cdot yr^{-1}$ reported by Derner et al. (1997), Reeder and Schuman (2002), Schuman et al. (1999), and Frank (2004) for other grassland areas. The results suggest that grazed Canadian grasslands have functioned as a net C sink during the prudent grazing management period, although broad uncertainties in these estimates existed as a consequence of high variation in experimental conditions and adaphic properties (Schuman et al. 2002; VandenBygaart et al. 2003). Although the SOC sequestration rates are relatively low, the grazing lands in Canada have provided a large C sequestration potential under its existing grazing regimes. The area of current native land for grazing in Canada is estimated at 12 700 000 ha (Table 2). Therefore, we estimated that, on average, about 2.41 $Tg \cdot C$ has been sequestered in the grazing grassland soils of Canada each year during the 50-yr restoration period of 1960—2011 (1 teragram$=10^{12}$ g). In addition, significant quadratic relationships of net C change ($P=0.0097$) and C change rate ($P=0.0137$) with respect to grazing duration were tested from the data (Fig. 3). Both net C change and C change rate increased with grazing length in the first 30 yr, reached an asymptote between 30 and 40 yr, and then decreased with grazing length after about 40 yr (Fig. 3). The asymptotical nature of net SOC change and SOC change rate to zero in recent years suggests the finite potential of soil carbon sequestration in Canadian grassland (Lal 2004).

Naturalized Grasslands

Drought in the 1930s led to a large area of cultivated land abandonment on the Canadian prairies. About 7 000 farmers abandoned their farmland from 1930 to 1938, representing 3 206 035 ha in three prairie provinces (Willms et al. 2011). Abandonment gave an opportunity for cultivated areas to success back to native vegetation as well as restore lost C. Other areas were seeded to perennial forages, including crested wheat grass (CWG; *Agropyron cristatum* [L.] Gaertn.) and Russian wild rye (RWR; *Psathyrostachys junceus* [Fisch.] Nevski), which supports livestock grazing. It is estimated that CWG was seeded to 77 000 ha by 1954 and about 1 000 000 ha by 1980s. RWR was seeded to 100 000 ha by the late 1970s (Dormaar et al. 1995). In this study, the actual measurements of net C sequestration or sequestration rate of either abandoned or naturalized (seeded CWG and RWR) grassland was unable to be estimated because of a lack of a C baseline estimate of cultivated Canadian rangeland during the 1930s. Nonetheless, the abandoned C restoration can be related to the difference in C stored in abandoned lands to C in native grassland from related studies. Natural restoration indicates considerable C restored in soils after abandonment ($P < 0.05$; Fig. 4). About 70 yr would be required to restore C back to a native level in Canadian grassland, agreeing with the required time of half a century estimate by Dormaar and Smoliak (1985). Although the C restoration after reseeding with CWG and RWR for several decades could not be known, C stored in the soils of the two perennials was estimated to be lower compared to the native level in the first 15 yr regardless of the years of previous cultivation (Broersma et al. 2000; Christian and Wilson 1999; Dormaar and Willms 2000; Whalen et al. 2003; Wang et al. 2010). CWG was ideally suited for rapid establishment in eroded semiarid areas, for high seed production, and for drought resistance, but a negative ecological impact has been evident through native species elimination, ecosystem biodiversity reduction, and insect explosions (Donahue et al. 2000).

Carbon sequestration led by conversions from various croplands to permanent grass cover is also well documented for Canadian agricultural soils. Two to 3.6 $Mg\,ha^{-1}$ C was gained in the 0–60-cm depth after seeded mixed grasses, of 7 and 14 species were sown on land previously cropped to wheat for 4 yr in Swift Current, Saskatchewan (Iwaasa et al. 2012); 2–15 $Mg\,ha^{-1}$ C was gained in the 0–15-cm, depth when CWG+Grama (*Bouteloua gracilis* [Willd. ex Kunth] Lag. ex Griffiths)+Alfalfa (*Medicago sativa* L.) were sown on land previously cropped to wheat for 20 yr in Meacham and Dana, Saskatchewan (Mensah et al. 2003); and 20–65 $Mg\,ha^{-1}$ C was gained in the 0–120-cm depth after seeding with mixed perennial grasses from annual cropping for 18 yr in southern Manitoba (Bell et al. 2012).

MANAGEMENT IMPLICATIONS

There has been a recent Canadian government focus to develop and implement mandatory GHG emissions reductions. Management practices that protect soils, water, and air tend to also support C sequestration. Results in our study showed that the Canadian natural grazing grasslands are likely acting as a carbon sink under current management regimes, but the potential of C sequestration is finite and has likely reached its saturation point in recent years. Challenges have emerged that have forced ranchers, park managers, researchers, and industry planners to propose improved management programs and legislation for sustainable development while providing both environmental and economic benefits related to all grassland services. As the greater use of native grasslands advances, more emphasis should be placed on protecting remnant native grassland ecosystem to enhance their productivity, biological biodiversity, drought and disease resistance, and soil C sequestration.

Light to moderate carrying capacity with adequate and uniform livestock distribution is recommended on the Canadian prairie grasslands. Deferring grazing during sensitive or vulnerable periods allows for more shoot and root reproduction, which is an effective way to maintain grassland health during drought cycles. In addition, a periodical moratorium from grazing could lead to restoration and would maintain grasslands in a healthy state. Similar regimes should also be placed on the natural grasslands in parks and other wildland conservation areas under the grazing of wild ungulates. Military bases in Canada provide protection for natural grasslands and associated ecosystems, including wildlife, endangered species, and dune complexes, but the potential fires, dry fuel load, and tank traffic require care. Shrub management is another key to maintain grasslands heath. The rapid encroachment of shrubs into most fertile soils covered by various mesic grasslands, northern parklands, foothills fescue, and tall prairies changes grassland structures and may also alter grassland soil C storage. Shrubs used for grazing as forages could be an effective way to reduce grazing pressure, which played an important role as complementary practices to grazing on Canadian grassland systems. Invasive weeds, including smooth bromegrass, Kentucky bluegrass, timothy, and crested wheatgrass, are key components in grassland management and should be carefully tested and controlled to maintain range health to avoid modifying physical or chemical attributes of grassland soils. Grasslands restoration has been treated as the most efficient method in achieving carbon restoration and CO_2 mitigation and has been applied broadly on deteriorated lands, some marginal land, and cultivated land on the Canadian prairie area, but applying the restoration programs should also carefully consider the balance between environmental benefit of society and economic benefits for agricultural production. For industry prospects, reclamation of natural grasslands after disturbance by oil, gas, mining, roads, pipeline, agriculture, and various other activities is essential for grassland health.

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