Potential of Rangelands to Sequester Carbon in Alberta

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Large amounts of organic carbon (C) are present in Alberta rangelands. One hectare of rangeland contains 50 to 200 tonnes (t) of carbon in soil organic matter, 2 to 10 t carbon in plant biomass and 1 to 2 t carbon in litter (Fig. 1). Total organic carbon levels in rangeland soils are considerably greater than the amount of carbon present in the atmosphere above these soils (15 t C ha^{-1}) or exchanged with the atmosphere each year (≈2 t C/ha). Total organic carbon in the 7 million hectares of native pasture in Alberta is equivalent to about three times the current annual emissions of all greenhouse gases in Canada.

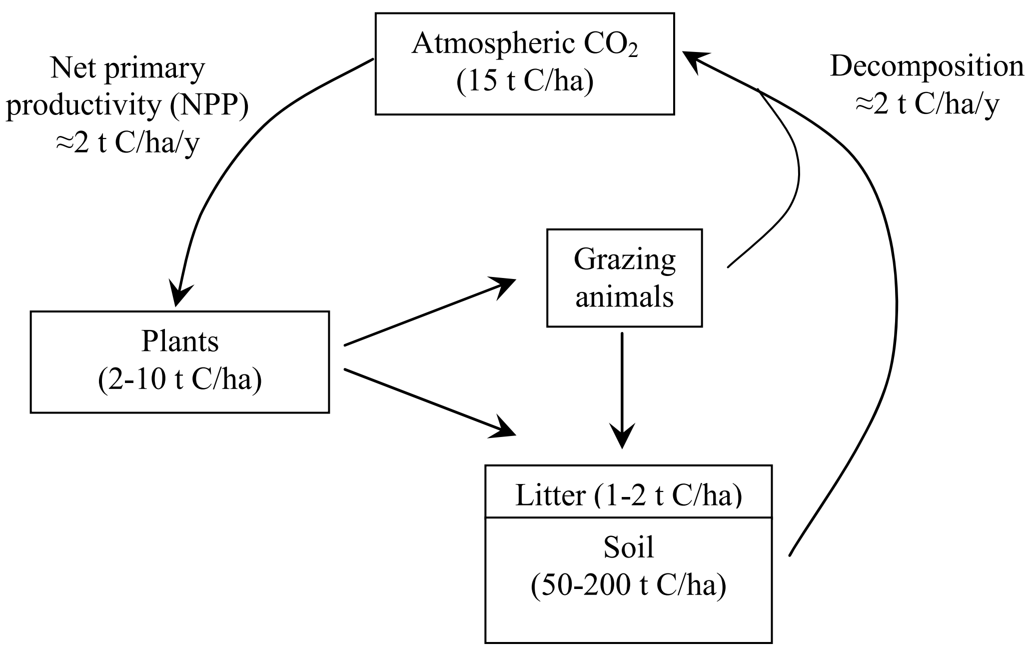

Fig. 1. Carbon flows in a typical Alberta rangeland. Small amounts of carbon may also be lost via animal weight gain, soil erosion and leaching.

Can Alberta rangelands be managed to store even more carbon? Several management options might be effective:

- Convert marginal cropland to rangeland
- Improve grazing management on rangeland that has been poorly managed
- Improve typical grazing practices (e.g., complementary or rotational grazing)

The effectiveness of these options depends on their ability to increase plant growth (net primary productivity) or reduce decomposition. The amount of carbon in an ecosystem depends on the historical balance between plant growth and decomposition. During initial plant establishment (e.g., following glaciation), organic carbon accumulates because carbon gains due to plant growth exceed carbon losses due to decomposition (Fig. 2). However, as organic carbon accumulates, decomposition increases until losses equal gains and the total amount of carbon in the ecosystem (the carbon inventory) achieves a constant value or steady state. Subsequent increases in plant growth or reductions in decomposition will increase the steady-state level of organic carbon, a process referred to as carbon sequestration.

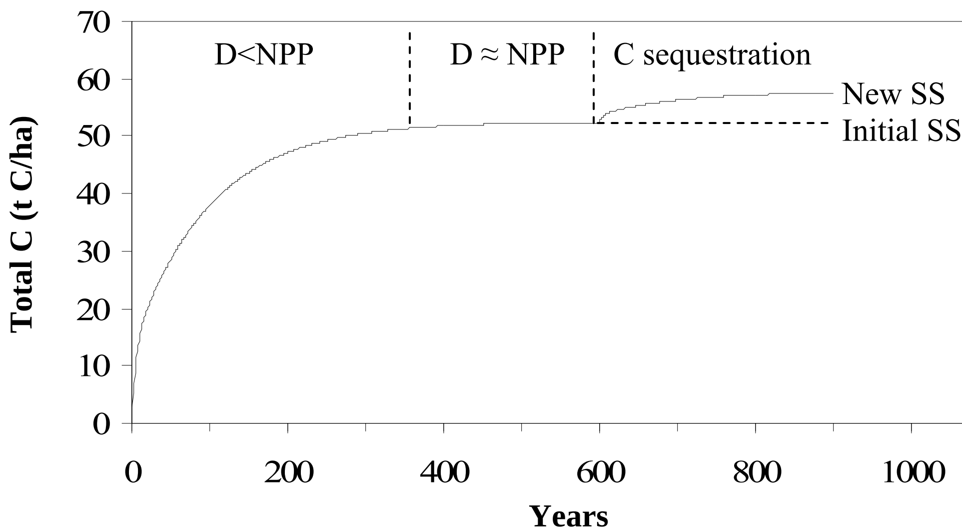

Fig. 2. Simple model illustrating carbon dynamics in a rangeland ecosystem. During soil formation, net primary productivity (NPP, 3 t C/ha/y in example) exceeds decomposition (D) and total soil carbon increases until D ≈ 3 t C/ha/y and total C is at steady state (SS). A 10% increase in NPP at year 600 increases total C by 10% over a 200-year period (C sequestration).

The level at which a steady state is achieved and the time required for this level to be achieved depends on the lifespan of carbon compounds in an ecosystem. Organic material that is easily decomposed (e.g., leaves) achieves steady state quickly and at low concentration. For example, organic material with a half-life of one year (y) (i.e., half of material decomposes within one year) added to soil at a rate of 1 t C/ha/y would attain steady-state within 5 years at 1.4 t C/ha. Addition of the same rate of organic material with a half-life of one hundred years would not attain steady state until 500 years, at 144 t C/ha. Soils contain a complex mixture of organic materials with half lives ranging from a few hours to many centuries. Simplified models with two to five carbon fractions and half lives ranging from 0.5 to 1000 y have successfully described the dynamics of soil organic carbon at timescales of years to millennia (e.g., Parton et al. 1988; Andrén and

Kätterer 1997). These models represent current understanding of how carbon inventories will change due to different environmental conditions or management practices.

Accurate measurements of carbon inventories are necessary to evaluate models and predictions of carbon sequestration. The following issues need to be considered for measurement of carbon inventories:

a) Measurements need to made on an area basis (e.g., t C/ha), not concentration (e.g., soil %C). The focus of many earlier studies was organic matter concentration, not inventory, and thus may not be reliable for carbon inventory estimates.

b) Carbon inventories need to be expressed on an equivalent mass basis when bulk densities vary between treatments (Ellert and Bettany 1995). For example, the simple action of tillage reduces surface bulk density and therefore would reduce the amount of measured carbon to specified depth. Soil carbon concentration might be more reliable in this example, but if soil carbon concentration declines with depth (it usually does), then the soil carbon concentration would increase after tillage because the effective depth of sampling is reduced. Earlier studies often overestimated the impact of conversion of native grassland to cropland because bulk densities were lower for cultivated soils (Davidson and Ackerman 1993).

c) All types of organic carbon that are likely to persist need to be measured. For example, more roots are present in native grasslands than croplands, but may not be included in measurements if the focus of the study was organic matter concentration.

d) The sampling program must be designed to measure small changes in carbon inventories in systems with a large carbon background. For example, based on sampling of uniform grass stands, Garten and Wullshleger (1999) estimated that a difference of 3 t C/ha could be detected with reasonable sampling intensity (n=16), but very large sample numbers (n>100) would be required to detect a difference of 1 t C/ha. Spatial variability in organic carbon inventories are often much greater in rangeland than cropland due to the wide range in vegetation types (grass, shrubs, trees) and complex landscapes. Repeated sampling of defined microplots may allow smaller changes in carbon storage to be quantified (Ellert et al 2002).

e) The depth of sampling must be sufficient to account for variations in carbon distribution with depth. For example, the sampling depth should be sufficient to include deep roots when comparing deep- and shallow-rooted grasses. Unfortunately, variability also increases with depth of sampling, and thus sampling intensity must also increase.

f) Soil erosion considerably complicates the evaluation of carbon sequestration. Soil erosion events are sporadic and highly variable over the landscape, and thus difficult to quantify. Eroded material is often enriched in carbon, but the level of enrichment is variable and difficult to predict. The decomposition rate of carbon in eroded material may be increased or decreased, depending on conditions at the site of deposition. Plant productivity may be affected at both the site of erosion and deposition.

g) Background changes in carbon storage may confound measurements of treatment effects. For example, without appropriate controls, carbon sequestration from a beneficial management practice may not be observed if a soil is still losing carbon due to initial cultivation. Slow changes due to climatic change (e.g., CO_2 enrichment) may not be distinguishable from slow changes due to land management.

h) The fate of organic carbon exported in agricultural products needs to be considered because not all exported carbon is released as CO_2. For example, grass harvested as hay may be fed to livestock in another region and increase soil carbon there through manure application.

i) The impact of conversion on other gases contributing to global warming potential (N_2O, CH_4) should also be considered. For example, the reduction in greenhouse gas emissions due to carbon sequestration during conversion of cropland to permanent cover was reduced by approximately 40% when impacts on N_2O and CH_4 were included in calculations (Boehm et al. 2004).

Potential to sequester carbon by converting cropland to rangeland

If pre-cultivation levels of organic carbon can be achieved after conversion of cropland to rangeland, then the potential for carbon sequestration can be estimated from the original loss of organic carbon upon cultivation. Based on sampling of 72 farms in Alberta, conversion of native vegetation to cropland reduced soil organic carbon by an average of 33 t C/ha (Fig. 3, McGill et al. 1988). The loss in soil organic carbon per unit area ranged from 24 t C/ha for Brown Chernozemic soils to 43 t C/ha for Gray Luvisolic soils. These estimates do not include losses in organic carbon due to reductions in the amount of organic carbon in root and litter. Comparable estimates of soil carbon sequestration for conversion of cropland to permanent cover (primarily tame pasture or hayland) determined using the Century model ranged from 18 t C/ha for the Brown soil zone to 66 t C/ha for Black and Gray soil zones (Boehm et al. 2004). Soil carbon increases when cropland is converted to native rangeland because less carbon is exported in agricultural products and both decomposition and soil erosion are slowed (Janzen et al. 1997).

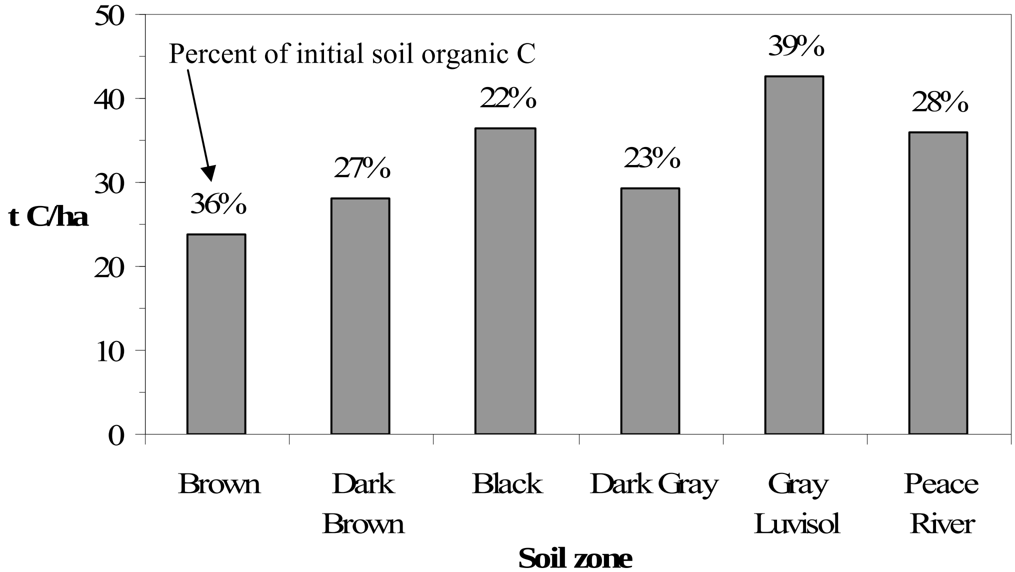

Fig. 3. Loss of soil organic carbon due to conversion of native rangeland to cropland (derived from McGill et al. 1988).

The time period required for organic carbon to recover to pre-cultivation levels may be considerable, particularly if appreciable carbon loss has occurred by soil erosion. In the Dry Mixedgrass Subregion, soil organic carbon was 12% lower for rangeland that had been cultivated for 10 to 15 years and then abandoned for 55 years than for rangeland under native vegetation (Dormaar and Smoliak 1985). Based on organic matter composition, Dormaar et al. (1990) estimated that recovery of abandoned cropland would take at least 75 years for the Dry Mixedgrass Subregion and 150 years for the Foothills Fescue Natural Subregion. Many centuries will be required to recover losses of highly stable carbon fractions (half-lives greater than 100 years) lost by soil erosion.

Potential to sequester carbon by improving grazing management

Rangeland managers control the intensity and timing of grazing by controlling when and how many grazing animals are stocked on an area of rangeland. These decisions affect carbon levels through impacts on net primary productivity, fate of plant residues, plant community structure and redistribution of nutrients through feces and urine.

Prevention of large animal grazing with exclosures, an extreme change in grazing practice included in many research trials, has relatively small impact on organic carbon levels compared to conversion to cropland (Figs. 3, 4). In a review of 236 studies, Milchunas and Lauenroth (1993) found that the impact of grazing was almost equally divided between positive and negative responses. In studies involving paired comparisons at multiple sites in Alberta and Saskatchewan, average organic carbon levels were not significantly different between grazed and ungrazed treatments (Fig. 3, Henderson et al. 2004; Colberg 2007). The lack of a consistent response can be attributed to the complexity of rangeland systems. Grazing generally reduces plant growth due to removal of plant biomass capable of photosynthesis, but moderate grazing may increase plant growth under some conditions through enhanced nutrient availability and changes in community structure (Milchunas and Lauenroth 1993). In a study conducted in the Dry Mixedgrass Subregion, Willms et al. (2002) found that grazed areas had lower plant growth than ungrazed areas in Chernozemic soils, but similar plant growth in Solonetzic soils. In a study conducted in the Mixedgrass Subregion, grazed areas under native vegetation that were dominated by blue grama had higher levels of organic carbon, but organic carbon levels were similar for grazed and ungrazed areas on land that had been broken and abandoned for a period of 60 years and had low levels of blue grama (Dormaar et al. 1994). Protection from grazing also affects litter accumulation, which in turn affects plant growth, decomposition and plant community composition (Schuman et al. 2002). Inconsistent response to protection from grazing can also be attributed to the variability in measurements. For example, differences in soil organic carbon due to grazing were not significant ($P \leq 0.05$) at any of the sites sampled by Henderson (2000) (Fig. 3). A difference in soil organic carbon of 13 t C/ha was also not significant ($P \leq 0.05$) in the study of Colberg (2007).

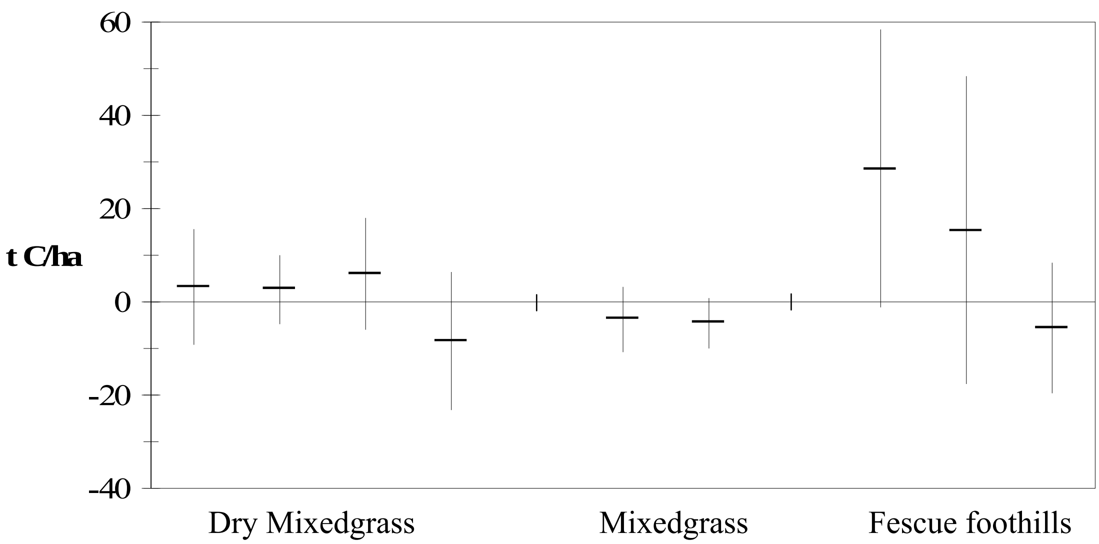

Fig. 4. Gain in total organic carbon in ungrazed exclosures compared to adjacent areas with moderate grazing at nine sites in southern Alberta (derived from Henderson 2000). Ungrazed exclosures were installed 20 to 71 years prior to measurements. Values above zero indicate that ungrazed exclosures had more carbon than grazed areas while values below zero indicate that grazed areas had more carbon than ungrazed exclosures. Error bars are 95% confidence limits.

Complexity and variability also make it difficult to quantify the impact of overgrazing on carbon levels. In general, overgrazing is expected to reduce carbon levels due to reduced plant growth and increased soil erosion (Schuman et al. 2002). However, responses in organic carbon to heavy grazing in long-term studies are inconsistent due to shifts in plant composition, interactions with weather and site characteristics, and measurement variability (Li et al. 200x; Johnston et al. 1971; Naeth et al. 1991; Dormaar and Willms 1998; Schuman et al. 2002; Ingram et al. 2008). For example, Ingram et al. (2008) found that organic C levels increased similarly for light and heavy grazed treatments during the first 11 years of a long-term study conducted in Wyoming (relative to an ungrazed control), but organic C levels declined substantially during the subsequent 10-year period (with increased drought) in the heavy grazed treatment, but not the light grazed or ungrazed treatments.

Rotational grazing involves frequent movement of grazing animals among small subdivisions of a pasture to obtain optimum vegetation use. In studies conducted in the Mixedgrass and Foothills Fescue Subregions with high stocking rates, range health declines and soil organic carbon concentrations decrease under rotational grazing (Dormaar et al. 1989; Willms et al. 1990). In a similar study in the Mixedgrass Subregion with low stocking rates, plant growth and soil organic carbon concentrations increased at a similar rate to those in ungrazed exclosures (Dormaar et al. 1997). The impact of rotational grazing on organic carbon levels likely depends on stocking rate and site characteristics.

Complementary grazing is a less intensive modification of rotational grazing that involves moving cattle to different pastures to improve pasture utilization and condition. For example, cattle may be grazed on tame pastures during spring and native pastures during summer to minimize negative impacts of spring grazing on native pastures. Based on a computer model, Lynch et al. (2005) estimated that adoption of complementary grazing would sequester 0.8 t C/ha over a 30-year period in the Aspen Parkland and Boreal Transition subregions. Boehm et al. (2004) used carbon sequestration estimates of 2 to 3 t C/ha for improved grazing practices (complementary and rotation grazing) in the montane cordillera, boreal plain and aspen parkland ecoregions. Measurement of these levels of carbon sequestration requires an intensive and well-designed sampling program, which has not yet been conducted in this region.

Although carbon levels in rangelands are likely close to steady-state, gradual changes may be occurring due to changes in environmental conditions (e.g., increased atmospheric CO_2 concentration, reduced fire frequency) and the long time period required for stable carbon forms to reach steady state. Based on 6-year monitoring of CO_2 fluxes in the mixedgrass prairie in North Dakota, Frank (2004) estimated that a moderately-grazed pasture may still be accumulating 0.3 t C/ha y^{-1}. Uncertainty in this type of measurement is high due to the small difference in net CO_2 flux relative to total CO_2 fluxes and to annual variability. Similar to the requirements for detecting carbon sequestration due to adoption of improved grazing practices, intensive and well-designed sampling programs would be required to detect changes of this magnitude.

Conclusions

Organic carbon stored in Alberta rangelands is equivalent to about three times the annual emissions of all greenhouse gases in Canada. The most certain and effective means to preserve this stored carbon is to maintain rangelands in good condition.

Increasing the amount of organic C stored in Alberta rangelands may be difficult because organic C levels are likely near maximum steady-state levels. Validation of an increase is also difficult because a small increase must be detected against a large, highly variable background. Numerous careful measurements are required to validate increases (or models that predict increases).

The most certain and effective method to increase carbon storage in rangelands is to convert cropland or extremely degraded rangelands to well-managed rangelands. Based on the measured differences in organic C between cropland and native rangeland, carbon storage should increase by 20 to 40 t C/ha when marginal cropland is converted to native rangeland. Much of this gain would be achieved within two to five decades, although long periods (centuries) may be required if considerable soil carbon has been lost via erosion.

The potential for improved grazing practices to increase carbon storage in rangelands is less clear. Even the differences in organic C levels between grazed and ungrazed areas are small and inconsistent, and very few measurements are available for less drastic changes in grazing management. Intensive and well-designed sampling programs would be required to quantify carbon sequestration from improved grazing practices.

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