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Soil carbon dynamics and potential carbon sequestration by rangelands

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"Capsule": *Grazing lands are estimated to contain 10–30% of the world's soil organic carbon.*

Abstract

The USA has about 336 Mha of grazing lands of which rangelands account for 48%. Changes in rangeland soil C can occur in response to a wide range of management and environmental factors. Grazing, fire, and fertilization have been shown to affect soil C storage in rangelands, as has converting marginal croplands into grasslands. Carbon losses due to soil erosion can influence soil C storage on rangelands both by reducing soil productivity in source areas and potentially increasing it in depositional areas, and by redistributing the C to areas where soil organic matter mineralization rates are different. Proper grazing management has been estimated to increase soil C storage on US rangelands from 0.1 to 0.3 Mg C $ha^{-1}year^{-1}$ and new grasslands have been shown to store as much as 0.6 Mg C $ha^{-1}year^{-1}$. Grazing lands are estimated to contain 10–30% of the world's soil organic carbon. Given the size of the C pool in grazing lands we need to better understand the current and potential effects of management on soil C storage. Published by Elsevier Science Ltd.

Keywords: C sequestration; Rangelands; Grazing; Management; Organic carbon

1. Introduction

The terrestrial biosphere contains about 1500 Pg of C in the surface meter of soil (Eswaran et al., 1995; Batjes, 1996) and another 600 Pg of C in the vegetation (Houghton, 1995; Schimel, 1995) which, together, is three times the amount of C found in the atmosphere. Therefore, any change in C storage in plants or soils has significant implications for atmospheric carbon dioxide. Rangelands (including grasslands, shrublands, deserts and tundra) occupy about half of the world's land area, and contain more than a third of above- and below-ground C reserves (Allen-Diaz, 1996). The USA has about 336 Mha of grazing lands of which rangelands account for about 48%. Changes in rangeland soil C can occur in response to a wide range of management and environmental factors. Given the size of the C pool in US rangelands we need to better understand the current and potential effects of management practices on soil C storage. Follett et al. (2001) present a broad review of the potential of U.S. grazing lands to sequester C.

2. Management effects on soil C

Within the past 10–15 years, numerous research projects have assessed the role of grazing and other management practices such as fire and fertilizer N application on the soil C balance of various rangeland ecosystems.

2.1. Grazing

Schuman et al. (1999) showed that grazing a northern mixed-grass prairie for 12 years at a light stocking rate or heavy stocking rate increased the mass of soil C in the surface 30 cm of the soil profile compared to non-grazed exclosures. The heavy stocking rate, 59 steer-days ha^{-1}, resulted in $<50\%$ utilization of the annual production of this rangeland and was about 1/3 above the rate recommended by the Natural Resources

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Conservation Service (NRCS) while the light stocking rate, 20 steer-days ha^{-1}, was about 35% below the NRCS recommended stocking rate. The increase in soil C storage averaged about 0.3 Mg $ha^{-1}year^{-1}$ in the surface 60 cm of the soil profile over the 12-year period.

Derner et al. (1997) also found increased soil C storage under grazed compared to ungrazed shortgrass steppe in northeastern Colorado. They found 1983 g m^{-2} in the grazed compared to 1321 g m^{-2} in the ungrazed treatments in the 0–15 cm soil depth and no differences in soil C in the 15–30 cm soil depth.

Povirk (1999) also showed a significant increase in soil C storage in an alpine meadow that had been grazed by sheep in the Medicine Bow National Forest in Wyoming. Soil organic C averaged 6.3% in the ungrazed treatment and 11% in the grazed treatment in the 0–7.5 cm soil surface. These mountain meadows are generally grazed for 1–3 months by sheep and/or cattle, and additional grazing by large wildlife herbivores such as elk, deer and moose.

Henderson (2000) measured soil organic C storage to a depth of 105 cm in grazed and ungrazed areas at nine native grassland sites on the southern Canadian prairies. In the surface soil layer (0–10 cm), organic C (excluding plant litter) tended to be higher in grazed than in ungrazed treatments, though the effect was significant at only two of the nine sites. In the entire soil profile, amount of C stored appeared to depend on moisture regime: at semi-arid sites (mean annual precipitation of 328–390 mm), soil C tended to be higher under grazing than in ungrazed exclosures; at subhumid sites (mean annual precipitation of 476 mm), the trend was reversed. The difference in total soil profile C between grazing treatments, however, were apparently not significant.

It is thought that well managed grazing stimulates growth of herbaceous species and improves nutrient cycling in grassland ecosystems. LeCain et al. (2000) reported increased early season (April–June) photosynthesis (as measured by chamber CO_2 exchange rates) on grazed northern mixed-grass prairie compared to ungrazed exclosures. Coupland and Van Dyne (1979) found that blue grama (*Bouteloua gracilis* (H.K.B.) Lag. Ex Steud.) dominated grasslands transfer more of the C to belowground plant parts. Frank et al. (1995) reported similar findings on a North Dakota northern mixed-grass ecosystem. Other researchers have found that grazing stimulates aboveground production (Mutz and Drawe, 1983; Dodd and Hopkins, 1985; Frank and McNaughton, 1993; McNaughton et al., 1996) and increases tillering and rhizome production (Floate, 1981; Schuman et al., 1990). Dyer and Bokhari (1976) also found that grazing may stimulate root respiration and root exudation rates. Livestock defecation and urination also significantly affect nutrient cycling and relocation in grazing systems. All of these factors may contribute to the observed increases in soil C storage. The grazing process also significantly impacts the rate of turnover/decomposition of the aboveground component of the plant community (litter, standing dead). Schuman et al. (1999) reported that under light and heavy grazing shoot turnover was 36 and 39% compared to 28% in ungrazed exclosures. They concluded that animal traffic may enhance the physical breakdown, soil incorporation and rate of decomposition of litter and standing dead plant material. Aboveground immobilization of C in standing dead plant materials in ungrazed rangelands may contribute to the lower soil C observed.

2.2. Fire

Rice (2000) reported that annual burning and grazing on the tallgrass prairie resulted in an increase in soil C storage of 2.2 Mg ha^{-1} after 10 year, which represents an increase of 0.22 Mg ha^{-1} $year^{-1}$. Burning of biomass can produce charcoal, a form of C very resistant to decomposition, which can account for a significant portion of the C stored in some grassland soils (Skjemstad et al., 1996). In some rangelands, fire management can influence the amount of C stored in biomass by altering the density or encroachment of woody species (Sampson and Scholes, 2000).

2.3. N fertilization

Many rangelands are N deficient and have been shown to exhibit increased production and increased water-use-efficiency in response to N additions. Fertilizer application can stimulate litter production, thereby enhancing soil C accumulation. For example, Rice (2000) reported that addition of N fertilizer increased plant production of the tallgrass prairie and resulted in an increase in soil C of 1.6 Mg ha^{-1}. Reeder et al. (1998) also showed increases in soil C in the surface 10 cm of a Phiferson sandy loam soil after 4 years as a result of annual applications of 34 kg N ha^{-1} on Conservation Reserve Lands seeded to a mixture of cool-season grasses. Application of other nutrients, where they are deficient, can also promote organic C storage (Nyborg et al., 1999; Conant et al., 2001). However, the benefits of increased soil C sequestration must be compared to the C costs of fertilizer production in order to determine the net effect on the atmosphere (Schlesinger, 1999).

3. Ecosystem variation and erosion effects

Any program to measure and manage for C sequestration on rangelands must deal with the incredible variability in soils and vegetation at multiple spatial scales ranging from the plant-interspace to the landscape. It must also account for the redistribution of soil C by soil erosion at multiple time scales.

Many arid and semiarid rangelands are characterized by patchy vegetation patterns. In some areas, the patches are most apparent at the plant-interspace scale (Schlesinger et al., 1990), while in other areas groups of plants aggregate, forming relatively fertile islands or bands in which both water infiltration and C accumulation are enhanced (Tongway and Ludwig, 1990; Ludwig et al., 2000). In some cases, these patches are associated with large differences in soil C that need to be accounted for in sampling, while in others, the differences are inconsequential relative to landscape-level differences.

The two types of variability are clearly illustrated by the data in Table 1 from the Jornada Experimental Range in northern Chihuahuan Desert (mean annual precipitation = 247 mm). The data represent soil %C and %N of the top 10 cm and are based on five samples from each vegetation strata (interspace, grass, and shrub) randomly selected from within a 1-ha plot at each site. At the sandy basin site, the mesquite (*Prosopis glandulosa*) and black grama- (*Bouteloua eriopoda*) dominated vegetation had a large, significant, positive effect on both soil C and N. At the alluvial fan site, which was dominated by creosote bush (*Larrea tridentata*) and bush muhly (*Muhlenbergia porteri*), C levels were over five times as high, but there was no apparent effect of vegetation strata on C, and only minimal effect on N. At both sites, N was highest under shrubs, but C was significantly higher under vegetation only at the sandy basin site. The plant interspace differences are probably a result of both increased inputs under the plants and redistribution of plant litter and soil by wind and water (Coppinger et al., 1991; Schlesinger et al., 1996; Vasquez de Aldana et al., 1996).

Soil erosion and deposition can also play a significant role at larger spatial scales. Over long time periods, it is responsible for generating many of the landscape-level differences in C sequestration potential: depositional areas tend to have soils with finer textures which retain more moisture (increasing production), and have a greater potential to physically protect soil organic matter from subsequent oxidation. Over shorter time scales, redistribution of soil organic matter by erosion can confound attempts to monitor changes at the landscape scale using plot-based approaches. Much of the soil organic C in many rangeland ecosystems is concentrated near the soil surface (Weaver et al., 1935), where it is also more susceptible to loss or redistribution by wind and water. Unless sampling points are spatially distributed based on relative areas of both erosional and depositional surfaces, erroneous conclusion can easily be drawn.

Table 1
Gravimetric C and N content for the top 10 cm of soil at two sites in south-central New Mexico

Site	% Carbon (s.e.)	% Nitrogen (s.e.)	C/N ratio (s.e.)
Sandy Basin			
Interspace	0.029 (0.002)	0.195 (0.036)	6.5 (0.8)
Grass	0.035 (0.001)	0.257 (0.017)	7.3 (0.4)
Shrub	0.040 (0.003)	0.326 (0.032)	8.1 (0.2)
Probability	0.015	0.026	0.159
Alluvial Fan			
Interspace	2.06 (0.12)	0.103 (0.003)	20.0 (0.9)
Grass	2.10 (0.12)	0.114 (0.004)	18.5 (0.8)
Shrub	1.98 (0.18)	0.119 (0.007)	16.6 (1.0)
Probability	0.850	0.091	0.055

4. Potential C sequestration by rangelands

Estimating potential C sequestration is more difficult for rangelands than for cultivated croplands. Rangelands include a wide diversity in plant communities, soils and landscapes. Furthermore, ecosystem responses are complex, because management practices may induce shifts in plant communities that may, over time, exert secondary effects on C storage. To date, long-term C responses to management have not been studied as extensively in rangelands as in cultivated systems, and only a few management scenarios under selected conditions have been documented. Nevertheless, the contribution of rangelands to C sequestration merits attention, despite the uncertainties, because rangelands occupy about twice the area of croplands in the USA. Estimates should be considered qualitative, however, and used more to highlight the potential role rangelands can play in C sequestration than as definitive predictions.

We (Schuman et al., 2001) estimated the potential impact rangelands could have on C sequestration on private and publicly managed rangelands. In making that assessment we made three assumptions: (1) that soil C reserves in any ecosystem, under consistent management and environment, eventually approach a steady-state value, and beyond that, rates of change in soil C are negligible from the standpoint of atmospheric CO_2 pools (Odum, 1969; Johnson, 1995); (2) change in the current trend of net C exchange (increasing or decreasing) depends on a shift in management or environmental conditions; and (3) minimizing losses of soil C is just as important as gaining soil C (Izaurralde et al., 2000). Using these assumptions, some of the data cited in this paper and others, and estimates of rangeland condition and acreages from the Natural Resources Conservation Service (NRCS), Bureau of Land Management (BLM), and the Forest Service (FS) we estimate that potential mitigated gains could account for 19 MMgC year^{-1} and avoided losses in soil C could account to 43 MMgC year^{-1} (Table 2).

Table 2
Estimated potential benefits to the mitigation of atmospheric CO_2 from the adoption of improved management of grasslands and potential avoided losses from grasslands in the USA (modified from Schuman et al., 2001)

Land use	Area (10^6 ha)	Rate[a] (Mg C ha^{-1} $year^{-1}$)	Rate[a] (MMg $year^{-1}$)
Potential mitigation gains			
Well managed grasslands[b]	57	0	0
Poorly managed grasslands[b]	113	0.1	11
CRP grasslands[c]	13	0.6	8
		Total gain	19
Potential avoided losses			
Well managed grasslands[b]	57	0.3	17
Poorly managed grasslands[b]	113	0.2	23
CRP grasslands[d]	13	0.3	4
		Total avoided loss	43

[a] Potential rates apply to possible changes in the period soon after a management change (or in the case of CRP lands, to current rates on 'existing' lands). Rates of accrual will diminish with time (perhaps after a few years or decades) as soil C approaches a new steady-state.

[b] According to USDA-NRCS (1998), 33% (54 Mha) of private US rangelands are reported to have no serious ecological or management problems, and 67% (109 Mha) would benefit from enhanced management or restoration. Of federally managed rangelands under the authority of the Bureau of Land Management, 37% (2 Mha) are in good to excellent condition and 63% (4 Mha) are in fair to poor condition (USDI-BLM, 1998). Eighty percent (0.8 Mha) of the National Grasslands in the Rocky Mountain Region managed by the USDA-FS meet plan objectives and 20% (0.2 Mha) are considered moving toward those objectives or not meeting nor moving toward plan objectives or undetermined (David Wheeler, Rocky Mountain Region, USDA-FS, Lakewood, CO, personal communication, 1999).

[c] CRP, Conservation Reserve Program, area and rate of potential C gain (from Bruce et al., 1999).

[d] Rate of avoided loss (0.3 MgC ha^{-1} $year^{-1}$) based on rate measured by Doran et al. (1998) at site converted from established CRP grassland to a no-till wheat-fallow system.

According to estimates by the USDA-NRCS (1998), USDI-BLM (1998), and the USDA-FS (David Wheeler, personal communication, 1999) about one-third of the US rangelands have no serious ecological or management problems; therefore, the soil C of these rangelands can be considered relatively stable, although fluctuations in species composition may lead to changes in C balance (Schuman et al., 1999). Two-thirds of the US rangelands are identified as having some constraints which limit productivity and hence, C storage. Potential soil C gains in these lands varies widely and any improvement will be slow and gradual. Therefore, we estimate these gradual gains at 0.1 MgC ha^{-1} $year^{-1}$ and 0.6 MgC ha^{-1} $year^{-1}$ for previously cultivated lands that have been reseeded to grass (Bruce et al., 1999). Bruce et al. (1999) estimate that lands under the CRP are gaining C at this higher rate, accounting for 8 MMgC $year^{-1}$. Therefore, the total potential gain in soil C from improved management of poorly managed rangelands (11 MMgC $year^{-1}$) and that derived from CRP grasslands (8 MMgC $year^{-1}$) could be as much as 19 MMg C $year^{-1}$.

As stated earlier, equally important as the gains in soil C storage are the avoided losses; therefore, preserving existing reserves is important. Recent studies (Manley et al., 1995; Schuman et al., 1999) have shown that properly grazed rangelands in Wyoming can gain soil C at a rate of 0.3 Mg C ha^{-1} $year^{-1}$ compared to ungrazed mixed-grass rangelands. Thus, maintenance of well-managed rangelands (rather than cessation of grazing as some advocate) would represent an additional 17 MMgC $year^{-1}$ that would not be lost. Similarly, soil C losses would not occur by maintaining current grazing strategies on 'poorly managed' rangelands and could account for an estimated 23 MMgC $year^{-1}$. Keeping all CRP lands in grass, rather than re-conversion to crop production, would also result in an avoided loss of 0.3 MgC ha^{-1} $year^{-1}$ (Doran et al., 1998) or about 4 MMgC $year^{-1}$. Thus, the total avoided losses from rangelands and CRP lands could account for about 43 MMgC $year^{-1}$.

These estimates are generally based on research done in the Great Plains and do not represent large areas of rangelands in the arctic, southwestern and eastern United States. Therefore, they should be viewed as an example of the magnitude of importance that rangelands could play in the mitigation of atmospheric CO_2, while increasing soil quality and soil productivity potential.

Recent soil C storage estimates published by the IPCC (Sampson and Scholes, 2000) related to land use, land-use change and forestry are broadly consistent with those used in developing estimates for US rangelands. The estimated rate of soil C gain to be achieved by management of grazing lands is 0.1 Mg C ha^{-1} $year^{-1}$ (0–0.3) for dry-temperate ecozones, and 1.0 Mg C ha^{-1} $year^{-1}$ (0.4–2.0) for wet-temperate ecozones. Their estimate of soil C gain from converting cropland to grasslands was 0.5 Mg C ha^{-1} $year^{-1}$ (0.3–0.8) for dry-temperate ecozones and 0.8 Mg C ha^{-1} $year^{-1}$

(0.5–1.0) for wet-temperate ecozones. Most US rangelands occur in dry-temperate ecozones.

5. Conclusions

Rangeland ecosystems are very complex, both in terms of vegetative community and soils, making it difficult to adequately characterize the soil C storage, and hence, short-term changes due to management or environmental changes. Soil erosion also can affect rangeland soil C distribution but generally does not result in soil C loss to the atmosphere. Erosion can cause changes in C storage if mineralization rates are different in source and depositional areas, or if reductions in plant productivity in source areas exceed gains in depositional areas.

Rangelands are a large repository of soil C because of their high C density and the vast land area they occupy. Throughout the world, improved rangeland management strategies and practices could greatly increase soil C sequestration, while greatly improving their production potential and other environmental benefits.

The estimates presented in this paper and those proposed by other scientists and world organizations are perhaps best viewed as illustrations of potential rather than quantitative values. However, these estimates do several things: (1) illustrate the significance of rangelands as a C sink, (2) demonstrate the potential increases in soil C storage that can be achieved with improved management and scientific understanding of soil C dynamics in rangelands, and (3) demonstrate the need for more research directed at understanding the mechanisms of management alternatives on C storage. As better research information becomes available, a more thorough and accurate estimation of C sequestration potential of rangelands can be achieved.

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