Grazing Land Contributions to Carbon Sequestration

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Key points

1. Grazing management can be used to increase soil organic carbon sequestration.
2. Grazing land soils contain large amounts of carbon with depth, and can store it for centuries.
3. Policies to encourage terrestrial carbon sequestration through conservation and good management of grazing lands are critical for many countries and the world.

Keywords: soil, rangeland, pasture, climate, policies

Introduction

The objectives of this paper are to provide a review of: (a) the influence of climatic factors and management practices on rates of carbon (C) accumulation and on long-term sequestration; (b) the potential contribution that grazing lands can make to C sequestration and soil C storage; and (c) policy issues and a current perspective of grazing lands in carbon credit trading. This paper will provide information about soil C accumulation and its long-term retention and as well as the influence of climate and management.

The term 'grazing lands' refers more to a set of highly diverse land resources than it does to a land use. Grazing lands include humid pastures that generally have more favourable climatic conditions and a greater potential to respond to management inputs. Grazing land also includes 'rangelands' which often include arid to semi-arid grazing lands, savannas, and shrub lands that are less responsive to management inputs. The term 'carbon sequestration' refers to the long-term storage of C in the terrestrial biosphere, underground, or the oceans, so that the build up of carbon dioxide (CO_2) in the earth's atmosphere will reduce or slow (http://cdiac2.esd.ornl.gov/, 2004).

Management and climate effects on carbon sequestration

Knowledge of soil organic carbon (SOC) sequestration information from grazing lands is limited, and predicting their sequestration potential is complicated by several factors including: wide regional and yearly climate variation; complexity of plant communities that vary from monocultures to an array of species; the presence and proportions of N fixing plants; type, species, and numbers of grazing animals; and management intensity and inputs (i.e. grazing and or mowing frequency, fertilising, and use of soil amendments).

Follett *et al.* (2001a) estimated that improving pastures in the US through fertiliser and/or manure application, liming, or planting improved forage species and proper grazing management, could result in the sequestration of 10.5 to 34.3 million metric tons (MMt) C/yr. These authors also predicted that improved rangeland management in the US could result in the additional sequestration of 5.4 to 16.0 MMt C/yr. A meta-analysis of 115 studies in pastures and other grazing lands worldwide (Conant *et al.*, 2001), indicated that soil carbon levels increased with improved management (primarily fertilisation, grazing management, and conversion from cultivation or native vegetation) in 74% of the studies considered, and that the greatest C sequestration occurred during the first 40 years following implementation of the management practice. With exception of a single irrigation study, the meta-analysis indicated that conversion of cultivated land to grazing land resulted in an average increase in SOC of 3-5%/yr (Conant *et al*., 2001). Soil C sequestration is generally greater under grazed pastures than under hayed pastures (Franzluebbers *et al*., 2000a). To increase SOC sequestration on rangelands generally requires improved grazing management, introduction of legumes, and control of undesirable species.

Grazing facilitates litter decomposition through the effects of grazing and animal traffic (Schuman *et al*., 1999). Removal of excess standing dead material by grazing increases the onset of spring growth and photosynthesis by enhancing sunlight penetration, and soil warming (LeCain *et al*., 2000). Good grazing management enhances rangeland productivity and maintains healthier rangelands (Schuman *et al*., 1999). Despite inherently low SOC sequestration rates, improved management of the world's extensive grazing lands provide a large C sequestration potential. Accurately measuring quantities of SOC in grazed pastures however is complicated by high spatial variability of the soil and vegetation, extensive land area, and the disproportionate redistribution of the nutrients in the dung and urine by grazing animals (Follett & Wilkinson, 1995; Franzluebbers *et al*., 2000b; West *et al*., 1989).

Soil management factors that improve plant productivity also contribute to increased SOC sequestration. Liming and the elimination of P deficiency have been shown to increase SOC (Ridley *et al*., 1990; Haynes & Williams, 1992). However, despite most rangelands being N-deficient and responding to N additions with increased production and water use efficiency, SOC often does not increase with increased N applications. The CCGRASS model (Van den Pol-van Dasselaar & Lantinga, 1995) predicts that low to moderate N applications lead to larger increases in SOC. Large N applications can result in less root production (Schnabel *et al*., 2001). Warm (C4) and cool (C3) season grasses often respond differently to N. In more humid climates, warm-season grasses produce more biomass and deposit more organic C than cool-season grasses with no or moderate N levels. Little difference is observed between the warm and cool season grasses with high fertility levels (Stout 1992; Stout & Jung, 1992, 1995; Wedin & Tilman, 1996). However, in more arid/semiarid climates, cool-season species respond to low N additions better than do the warm-season species. Adding legumes to grazing lands can increase N availability and plant biomass production, but SOC increases may be smaller than expected due to production of low C:N organic matter which is more readily decomposed (Schnabel *et al*., 2001). This response is influenced by the climatic regime of the region. Mortenson *et al*. (2004) found that *Medicago sativa* ssp. *falcata* interseeded into rangelands in the US Northern Great Plains significantly increased SOC sequestration and soil N levels.

A review of the literature and evaluation of SOC status and dynamics in grazing land soils of the eastern US led Schnabel *et al*. (2001) to an evaluation of the general effects of various conditions and pasture management practices on SOC sequestration. The magnitude and duration of management effects shown in Table 1 depend on several factors such as climate, soils, previous management or potential net primary productivity (NPP). Converting marginal cropland to pastureland will increase SOC. Changes in how animals, plants, and soils are managed can also affect the balance between C inputs to the soil via plant fixation and losses of SOC to the atmosphere via decomposition. Where pasturelands are highly productive and SOC is already high, small or no increases in C storage may be expected. Larger increases can be made on marginally productive pasturelands by improving soil fertility or animal management to enhance plant productivity (Table 1).

Table 1 The effects of pasture management methods on C storage in soil of eastern US pasturelands (Schnabel *et al*., 2001)

Factor	Measured effect on pastureland	Measured or inferred effect on C storage in soil
Animal management		
Grazing lands	More C returned to soil for rapid incorporation.	Increase SOC[1].
Intensive grazing	With adequate moisture, intensive management increases NPP[2], increased foot traffic breaks down residue.	Increase SOC.
	With limited moisture, increased stocking can damage stands.	Decrease SOC.
Forage management		
Replacing C3 grasses with C4 grasses	At low to moderate fertility, increase NPP and reduce forage quality.	Increase SOC.
	At high fertility, little change in NPP.	Little change in SOC. May not be sustainable.
Replace endophyte infected fescue with uninfected fescue	Increase forage quality.	Decrease SOC.
Increase harvest frequency	Reduce NPP, increase forage quality.	Decrease SOC.
Delay harvest or grazing	Reduce forage quality.	Increase SOC.
Soil Management		
Liming	Increases P availability and NPP.	Increases SOC.
P fertilisation	If P deficient, increase NPP.	Increase SOC.
	If P is adequate or in excess, no change.	No change.
N fertilisation	Low inherent fertility, increase NPP and forage quality.	Increase SOC.
	High inherent fertility; NPP, and decomposition of SOC, no change or increase.	No change, decrease, or increase in SOC, depending on relative change in NPP and decomposition.
Manuring	Increases NPP if fertility limits growth.	Increases SOC.
Drainage	Increases NPP, increases SOC decomposition.	Decreases SOC.

[1]SOC = Soil organic carbon; [2]NPP = Net primary productivity

Information from US Great Plains rangelands indicates that stocking rates can impact on soil characteristics and plant species composition and, in turn, SOC storage (Bauer *et al*., 1987; Frank *et al*., 1995; Schuman *et al*., 1999; Potter *et al*., 2001). Schuman & Derner (2004) recently summarized the current state of knowledge about the effects of management practices on SOC sequestration in rangelands (Table 2).

Grazing of semi-arid rangelands generally benefits or has a neutral effect upon SOC sequestration in both shortgrass steppe and mixed-grass prairie regions. However, some grasslands in the arid southwestern US, such as *Bouteloua eriopoda* (Torr.) Torr. (black grama) dominated communities, do not tolerate grazing disturbance and when lost will not return to their previous condition even with human intervention (Kephart *et al*., 1995).

Northern mixed-grass rangelands in Wyoming exhibited plant community composition shifts toward warm-season (C4) species when season-long heavy stocking rates were imposed

(Manley *et al*., 1995; Schuman *et al*., 1999). Aboveground biomass also decreased after 10 years in those pastures grazed at heavy stocking rates, mainly as a result of the loss of the more productive cool-season (C3) grasses. Increases in SOC can result from this plant community shift (Reeder & Schuman 2002; Smoliak *et al*., 1972; Frank *et al*., 1995) because of the more dense and shallow root system of the dominant C4 species *Bouteloua gracilis*. Interseeding of *Medicago sativa* spp. *falcata* (yellow flowered alfalfa) into northern mixed-grass rangeland, significantly increased SOC sequestration (Mortensen *et al*., 2004). Fire, a naturally occurring ecological process in tallgrass prairie, controls the spread of woody species and benefits SOC sequestration (Rice, 2000; Sampson & Scholes, 2000).

Table 2 Rangeland management effects on soil carbon sequestration rates

Management	Ecosystem	Soil C sequestration	Location	Citation
Grazing	Shortgrass steppe.	0.07-0.12 Mt C/ha per year.	Colorado	(1)
	Northern mixed-grass prairie.	0.30 Mt C/ha per year.	Wyoming N. Dakota	(2, 3, 4)
	Southern mixed-grass prairie.	No change in C.	Oklahoma	(5)
	Canadian prairie.	Higher SOC^1 when grazed.	Canada	(6)
Nitrogen inputs	N-fertilization of tall grass prairie.	1.6 Mt C/ha per year.	Kansas	(7)
	N and S fertilization of northern prairie.	Increases of 0.45-0.72 Mt C/ha per year.	Saskatchewan	(8)
	Legume interseeded mixed-grass prairie.	0.33-1.56 Mt C/ha per year.	South Dakota	(9)
Fire	Tall grass prairie.	0.22 Mt C/ha per year.	Kansas	(7)
Restoration of degraded lands	Southern mixed-grass prairie.	Moderate grazing, no change; Heavy grazing, 65% decrease.	Oklahoma	(5)
	Marginal cropland to grazing land.	Restored soil C to 80% of native rangeland in100 years.	Sudan	(10)
	Restored semiarid savanna.	Increases of 1.9-2.75 Mt C/ha per year.	Argentina	(11)
	Southern tall grass prairie.	Avg. = 0.45 Mt C/ha per year.	Texas	(12)
	US Great Plains (CRP^2). Introduced grasses.	0.8-1.1 Mt C/ha per year.	Texas, Kansas, Nebraska, N. Dakota	(13, 14)
	Mined land reclamation.	1.95 Mt C/ha per year.	Wyoming	(15)
Woody plant encroachment	Southern mixed-grass prairie.	Remove *Prosopis glandulosa* but no affect on soil C.	Texas	(16)
	Subtropical savanna.	0.23 Mt C/ha per year under woody plants (model predictions).	Texas	(17)
	Mesquite-acacia savanna.	0.14 Mt C/ha per year.	Texas	(18)

^{1}SOC = Soil organic carbon; ^{2}CRP = Conservation Reserve Program

(1) Derner *et al.,* 1997; (2) Reeder & Schuman, 2002; (3) Schuman *et al*., 1999; (4) Frank, 2004; (5) Fuhlendorf *et al*., 2002; (6) Henderson *et al*., 2004; (7) Rice, 2000; (8) Nyborg *et al*., 1994; (9) Mortensen *et al*., 2004; (10) Olsson & Ardo, 2002; (11) Abril & Bucher, 2001; (12) Potter *et al*., 1999; (13) Gebhart *et al*., 1994; (14) Follett *et al*., 2001b; (15) Stahl *et al*., 2003; (16) Teague *et al*., 1999; (17) Hibbard *et al*., 2001; (18) Liao, 2004.

Degraded rangelands can lose significant amounts of SOC, but in some ecosystems have substantial potential (with proper management) to sequester SOC to replace that lost. The C4-dominated grazing lands/savannas of southern Texas have been transformed to ‘thorn woodlands’ as tree and shrub abundance (primarily *Prosopis glandulosa* ‘honey mesquite’) has markedly increased in the past century (Liao, 2004). Model predictions estimate a 2-fold increase in SOC in the top 10 cm of the soil profile beneath clusters of woody plants (23.5 Mt C/ha) compared to open herbaceous vegetation (11.7 Mt C/ha) (Hibbard, *et al*., 2001). They estimated a soil C sequestration rate of 0.23 Mt C/ha/yr for the woody plants. Field research addressing SOC storage following woody plant invasion in the Rio Grande Plains of southern Texas, generally corroborates the above model predictions (soil organic C to a depth of 30 cm was >50 Mt C/ha for woody plants and about 20 Mt C/ha in grasslands) (Liao, 2004).

Large stocks of SOC are present in the historic grazing land soils in the US Great Plains. Reseeding with grasses as a permanent cover on previously cropped soil, is carried out on an extensive basis in the US, in response to the Conservation Reserve Program (CRP), run by the US Department of Agriculture (Food Security Act of 1985 (P.L. 98-198)). The CRP is a voluntary program where landowners enrol in contracts to take vulnerable croplands or environmentally sensitive lands out of agricultural production. The current cap is 15.9 M ha, with approximately 13.6 M ha of this land currently planted to grasses.

Follett *et al*. (2001b) compared cropped and CRP land across the mid-continental US region (extending from near the Canadian border into Texas), representing approximately 5.6 M ha. The sites chosen were fields that had been reseeded as part of the CRP programme for a minimum of 5 years (average 7.9 years), and were paired with adjacent fields that had been in long-term cropping. A rapid rebuilding of the near-surface soil C stocks was observed (Table 3), averaging 570, 740, and 910 kg C/ha per year for the 0-to 5, 0-to 10, and 0-to 20 cm depth increments respectively. However, they did not reach the level of C stocks observed in paired native grass fields. In addition, research under turf grass by Qian & Follett (2002), indicates that total C sequestration increased at a nearly constant rate for 30 years.

Table 3 Average weight at different depths of soil organic carbon (Mt/ha) across 14 sites in 9 Great Plains states in the US. Reseeded conservation reserve programme sites were in permanent grass cover for at least 5 (average of 7.9) years (Follett *et al*., 2001b)

Depth (cm)	Mt/ha		
	Native	Reseeded	Cropped
0-5	16.7	13.0	9.0
0-10	29.0	23.2	18.3
0-20	45.0	39.7	32.2
0-30	60.2	52.8	45.0
0-60	84.9	75.8	67.8
0-100	91.4	89.8	81.0

Sequestered SOC can if undisturbed, remain in the soil for centuries. Data in Figure 1 is for three native prairie sites along a 1300 km north to south transect of the US Great Plains where SOC was ^{14}C dated (Follett *et al*., 2004). These data show that during the Holocene (beginning ~ 12,000 calendar years before present (YBP)), except where eolian disturbance had resulted in over- and under- layering of soil horizons, mean residence time (MRT) of SOC in the soil increased, but its concentration decreased with depth. Even though it decreased with depth, substantial amounts of SOC still remained, even after thousands of years.

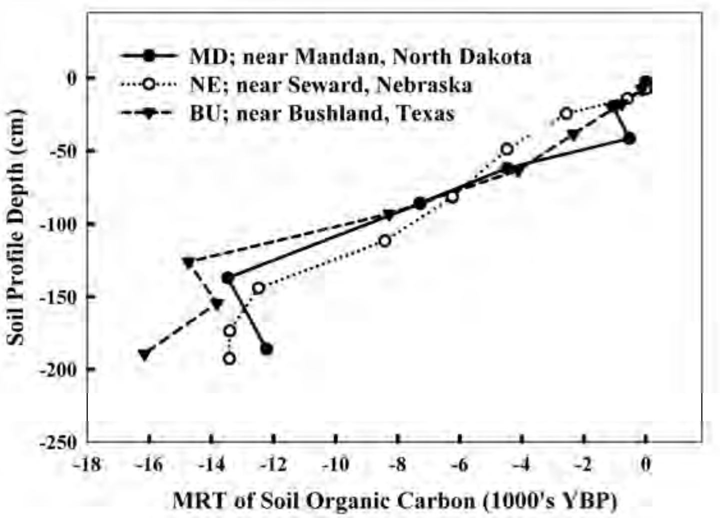

Figure 1 Mean residence time (MRT) of the soil organic carbon (SOC) with soil profile depth across a north to south transect of the US Great Plain from the State of North Dakota to the State of Texas

Potential contribution of world grazing lands to soil C sequestration and storage

This paper aims to present a worldwide view of the topic of SOC sequestration in grazing lands. However, the availability of such information around the world is quite limited, particularly in less-developed countries. Nonetheless, much information and insight can be obtained from FAO (2004) for the various regions of the world. In contrast to the previous discussion of pastures and rangelands, FAO describes ‘permanent pasture’ (Table 4) as land used permanently ($\geq$ 5 years) for herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land). Permanent pasture and the category ‘forests and woodland’; is vague - especially for shrub land and savanna which may be reported under either category. The National Institute of Public Health and the Environment (RIVM) in the Netherlands grouped 238 countries into 19 regions (Kreileman *et al.*, 1998) that are used in the following discussion. The reader is referred to this report for countries included in each region, but RIVM region 19 (Antarctica) is excluded (Table 4 and 5).

Conant *et al.* (2001) reviewed results from 115 studies in 17 countries on the effects on SOC, of grazing management and conversion into grazing land. Evidence that SOC sequestration under grasslands can be enhanced by fertilisation, improved grazing management and grass species, conversion of cultivated land to permanent grass cover, presence of legumes, introduction of earthworm, and irrigation was identified (Conant *et al.*, 2001; Follett *et al.*, 2001a; Schuman & Derner, 2004). Although many important grassland areas were not represented, reported rates of sequestration ranged from –0.2 to +3.0 Mt C/ha per year.

Table 4 Agricultural land and pasture area, percent pasture to agricultural land area, N-fertiliser consumption, and N-consumption per unit of agricultural land area for World RIVM regions (Kreileman *et al.*, 1998)

RIVM No.	RIVM Region	Agricultural land area (1000 ha)	Permanent pasture (1000 ha)	Pastr/agric land area (%)	N-fertiliser consumption (t)	N-consumption/ Ag. land area (kg/ha)	Region/ World pasture area (%)
	World	5,011,700	3,488,120	69.6	80,948,904	16.2	-
1	Canada	74,700	29,000	38.8	1,564,348	20.9	0.8
2	United States	412,880	234,000	56.7	10,464,065	25.3	6.7
3	Central America	144,481	98,915	68.5	1,920,422	13.3	2.8
4	South America	639,388	513,950	80.4	3,246,436	5.1	14.7
5	North Africa	118,639	75,210	63.4	1,419,116	12.0	2.2
6	West Africa	143,964	103,663	72.0	124,840	0.9	3.0
7	East Africa	287,736	240,373	83.5	209,314	0.7	6.9
8	Southern Africa	373,462	332,778	89.1	580,743	1.6	9.5
9	OECD Europe	145,915	59,614	40.9	9,328,614	63.9	1.7
10	Eastern Europe	65,775	19,540	29.7	2,300,168	35.0	0.6
11	Former USSR	568,801	360,309	63.4	2,553,327	4.5	10.3
12	Middle East	318,898	257,400	80.7	3,089,686	9.7	7.4
13	South Asia	262,540	49,123	18.7	14,394,896	54.8	1.4
14	East Asia	683,951	529,399	77.4	22,719,085	33.2	15.2
15	Southeast Asia	110,409	17,032	15.4	5,222,997	47.3	0.5
16	Oceania	475,117	419,470	88.3	1,192,868	2.5	12.0
17	Japan	5,235	405	7.7	487,400	93.1	0.0
18	Greenland	235	235	100.0	-	0.0	0.0

Data obtained from FAO (2004).

Table 5 Total meat, meat from all grazing livestock, and meat from only sheep + goat + beef + buffalo (grazing animals) in metric tons (Mt) and as percentages for the World and within 18 RIVM regions (Kreileman *et al.*, 1998)

RIVM No.	RIVM Region	Total meat produced (Mt)	Meat from grazing livestock (Mt)	Meat from beef, sheep, goat and buffalo (Mt)	Meat from beef, sheep, goat and buffalo/meat from ALL grazing livestock (%)	Meat from beef, sheep, goat and buffalo/TOTAL meat (%)
	World	233,962,789	73,557,786	71,220,329	96.8	30.4
1	Canada	3,999,816	1,293,298	1,275,298	98.6	31.9
2	United States	37,640,452	12,627,850	12,404,100	98.2	33.0
3	Central America	6,359,620	2,161,055	2,070,839	95.8	32.6
4	South America	25,064,433	12,323,472	12,156,423	98.6	48.5
5	North Africa	2,906,326	1,499,308	1,412,589	94.2	48.6
6	West Africa	1,237,310	819,796	620,711	75.7	50.2
7	East Africa	2,517,863	1,944,790	1,745,619	89.8	69.3
8	Southern Africa	2,809,418	1,582,838	1,466,038	92.6	52.2
9	OECD Europe	36,688,554	9,066,084	8,840,280	97.5	24.1
10	Eastern Europe	7,997,711	1,320,213	1,281,061	97.0	16.0
11	Former USSR	8,827,797	4,601,328	4,510,872	98.0	51.1
12	Middle East	5,375,214	2,352,198	2,271,414	96.6	42.3
13	South Asia	7,867,328	5,510,959	5,510,959	100.0	70.0
14	East Asia	65,303,182	9,115,466	8,668,966	95.1	13.3
15	Southeast Asia	9,250,641	1,438,898	1,433,864	99.6	15.5
16	Oceania	5,111,619	3,876,097	3,807,027	98.2	74.5
17	Japan	3,005,930	537,709	530,705	98.7	17.7
18	Greenland	608	402	402	100.0	66.1

Data obtained from FAO (2004).

Total meat production from domestic livestock; meat from grazing livestock (sheep, goat, beef, buffalo, game animal, horse, ass, mule, camel, and other camelid); and meat only from sheep, goat, beef, and buffalo for the year 2000 are shown in Table 5. Sheep, goat, beef, and buffalo are the dominant grazing animals from which the world's meat is produced and account for 76 - 100% of grazing livestock meat, and between 13 and 69% of all meat production. Production of sheep, goat, beef, and buffalo ('grazing animal') meat per unit area of permanent pasture should provide a proxy of pasture productivity as influenced by climatic potential, forage productivity, and the husbandry skills of the indigenous grazing animal operations by RIVM region. A general measure of production improvement in RIVM regions may be indicative of N-fertiliser use per unit area of agricultural land in those regions.

The regression of grazing animal meat production on N-fertiliser use produces an r^2 of 0.88 (Figure 2). Japan (RIVM region 17) is not included in the analysis because of its high rate of N consumption per unit of agricultural land, and high rate of grazing animal meat production per unit of permanent pasture (Tables 4 and 5). Regions are identified (Figure 2) wherein grazing livestock meat production was >20 kg/ha, representing conditions (climate, soils, grazing management, and other management inputs) potentially favourable for SOC sequestration. The area of permanent pasture in these ten RIVM regions (1, 2, 3, 4, 5, 9, 10, 13, 14, and 15) includes that from 119 countries (FAO, 2004) and represents approximately 1,625 million ha (46.6%) of the world's permanent pasture land.

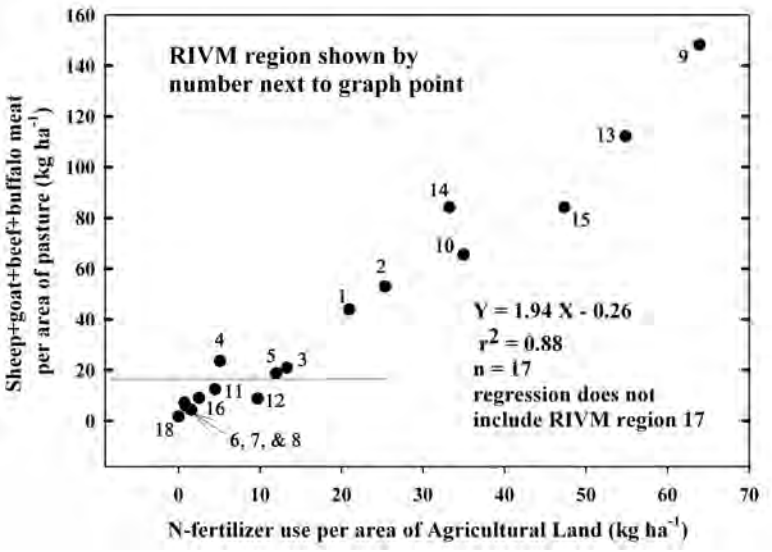

Figure 2 Meat production from grazing animals (sheep, goat, beef, and buffalo) per unit area of permanent pasture (FAO, 2004) as a function of N-fertilizer use per unit area of agricultural land

Within an individual RIVM region, there can be a wide diversity of climate, soils, and other factors. Based upon grazing animal meat production, it might be assumed that forage production per unit of pasture area would be higher with improved inputs and grazing management, which would increase the potential SOC sequestration rate. For example, in RIVM 3 (Central America), N-fertiliser consumption/ha of agricultural land and, grazing animal meat production/ha are lower than in many other RIVM regions (Figure 2, Tables 4 and 5). However, there are a number of forages that, when introduced and managed, produce high forage yields with high digestibility. It has been known for a long time (Vicente-Chandler *et al*., 1964) that the potential for forage, and hence cattle production in vast areas of the humid tropics with year-round warm weather, high rainfall, and deep porous soils is not being achieved. Vicente-Chandler *et al*. (1964, 1983) in Puerto Rico increased yields of dry forage from approximately 5.6 Mt/ha of poor quality forage to 45 Mt/ha of excellent-quality forage, by using improved grasses, heavy fertilization, liming, weed control, intensive utilisation systems, and careful management. The year-round carrying capacity reported by (Vicente-Chandler *et al*., 1983) was 10 cows/ha and 5 cattle/ha (average weight 270kg). Development of such systems with improved fertility and plant species has the potential to provide high amounts of meat from grazing animals and yet to conserve soil and water resources. Vicente-Chandler *et al*. (1983) considered that their techniques, and the potential of the system for forage and grazing were "applicable to similar vast humid tropical areas of South America, Africa, southeast Asia, Borneo, Australia, and the Antilles." Even though forage and beef production were high in these studies, soil organic matter content decreased from about 6.7% from the virgin forest soil, to 3.7% after 15 years under unfertilised volunteer pasture (Vicente-Chandler *et al*., 1964; 1983). Unfortunately, no measures of rates of SOC change under the high-fertility, well managed and grazed pastures were reported.

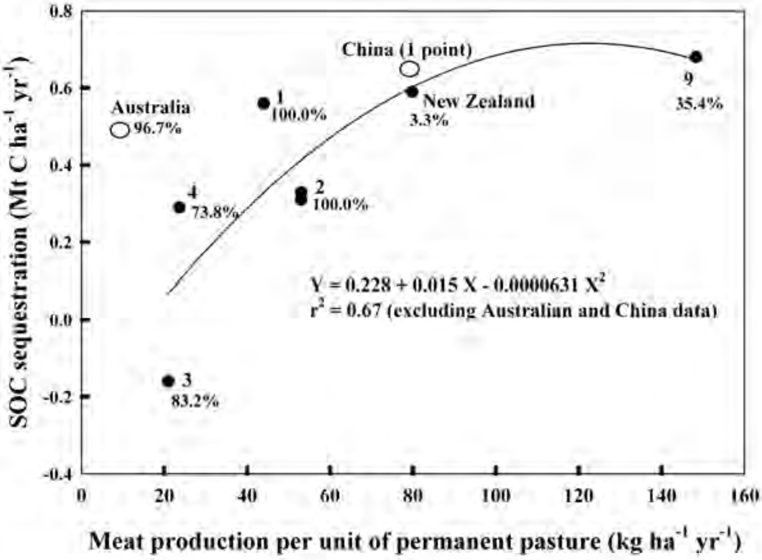

Figure 3 Average rates of SOC sequestration for countries in RIVM regions reported by Conant *et al*. (2001) as a function of meat production per unit of permanent pasture calculated from FAO (2004) data

Conant *et al*. (2001) reviewed research literature, and reported rates of SOC sequestration from individual countries that were located in RIVM regions 1, 2, 3, 4, 9, 14, and 16. In addition, Follett *et al*. (2001a) obtained estimates of C sequestration rates in US grazing lands (RIVM 2). Figure 3 shows the average rate of SOC sequestration from Conant *et al*. (2001) and the corresponding RIVM region number, plotted against meat production from grazing animals per unit of permanent pasture (FAO 2004). The % shown near the region number is the amount of pasture area within the RIVM region that is represented by the countries for which Conant *et al*. (2001) had data. For the USA (RIVM 2), Conant's data is shown as the lower point and the data for Follett *et al*. (2001a) the slightly higher upper point. Only four data points (from China) were available for RIVM 14, of which 3 were deep cores that could be expected to mask near surface C sequestration rates, and one point that lay near the regression line, Figure 3. As so few points exist for RIVM 14, they were not included in the regression. Australia and New Zealand comprise RIVM 16. The Australian data showed reasonably high rates of SOC sequestration, but meat production per unit of permanent pasture was low (indicating a breakdown in the relationship), possibly because reported experimental C sequestration data was from productive pastures that were not representative of the large dry-climate areas of Australian permanent pasture reported by FAO (2004). In contrast, New Zealand data with wetter-climate pasture areas was consistent with the relationship (Figure 3) and was included.

The quadratic regression equation ($r^2 = 0.67$) that is shown in Figure 3 does not include the Australian or Chinese data. Also, this equation does not necessarily represent sequestration rates in *all* countries and regions of the world. However, the world's rate of grazing animal production is 0.02 Mt meat/ha per year, which if used in the quadratic equation in Figure 3 results in an estimate of the world's SOC sequestration rate on permanent pasture areas of 0.06 Mt C/ha per year. If multiplied by the world's area of permanent pasture (from Table 4), amounts to 0.2 Gt SOC sequestration/yr on 3.5 billion ha of permanent pasture. For comparison, the world's SOC sequestration potential is estimated to be 0.01 to 0.3 Gt SOC/yr on 3.7 billion ha of permanent pasture (Lal, 2004). Thus SOC sequestration by the world's permanent pastures can potentially offset up to 4% of global greenhouse emissions.

Policies

Broadly speaking, possible strategies to lower or control atmospheric carbon dioxide (CO_2) concentration might include reduction in; fossil fuel use, 'separation and capture', deep ocean sequestration, injection into oil and gas geologic formations where the resource has been removed, or advanced biological processes for atmospheric CO_2 removal. Associated policies for CO_2 reduction programmes may include regulation. Some of the above strategies are currently cost prohibitive or may have declining cost:benefit relations. Markets trading in environmental commodities have existed since 2002, especially in the European Union countries. Such markets are now developing in the US, but the low value of C (< \$1 Mt CO_2) results in it being mostly an experimental market that has the potential to increase if future caps or regulation were to occur (Lal, 2004). In the mean time, international negotiations and agreements, such as the 'Framework Convention on Climate Change (1994)', the Kyoto Protocol and the World Trade Organization will continue to influence the direction of international policies and agreements.

Policies to encourage SOC sequestration by agriculture (including grassland soils) have several advantages for atmospheric CO_2 reduction. Chief amongst these are that they can be implemented quickly with existing technology, and with minimal impact on the economic system. It also has high co-benefits for the environment such as improved soil quality, soil erosion reduction, and improved water quality. An additional attraction is as a potential source of income to agricultural producers, especially if the economic value of the sequestered SOC had a modest trading cost of $20/Mt (Lal, *et al*., 2003). This higher value would rapidly stimulate the market and the rate at which co-benefits to the environment would be realized. However, these co-benefits and the amounts of SOC that can be sequestered with better management are likely to be greater for cultivated soils than for grazing lands (Lal, 2004). Sperow *et al*. (2003) estimate that US cropland soils could sequester 60-70 million Mt C/yr, and Follett *et al*. (2001a) estimate an average sequestration rate of 54 million Mt C/yr for USA grasslands. Policies and programs that encourage conservation of current grazing lands and conversion of marginally productive croplands to perennial vegetation are critical factors that can contribute to the sequestration of the potentially large amounts of SOC stored by these ecosystems.

Finally, it is highly probable that greenhouse gas emission policies in the US will differ from those of countries who agree to the Kyoto protocol. However, the US will encourage reduction in atmospheric CO_2 levels. Policy initiatives such as ‘Clear Skies’ are designed to reduce emissions of sulphur dioxide, mercury and nitrogen oxides; allow ‘Cap and trade - Market-based approaches’; and reduce greenhouse gas intensity. Rates of greenhouse gas (GHG) emission and atmospheric CO_2 reduction will probably be market driven. Programmes within the US Department of Agriculture (USDA) will likely be implemented under USDA’s conservation programmes, and will result in the development of methods to estimate sources and sinks of agricultural and forestry GHGs. These programmes will support voluntary agreements with the private sector and support development of technologies and practices that enhance SOC sequestration. An example is the Environmental Quality Incentive Programme (EQIP) of USDA which is a cost-share programme to promote resource conservation on working farms, and allows USDA to provide national guidance to make GHGs a priority resource concern, and which has the goal of reducing GHG emissions by 9.1 million Mt carbon equivalent by 2012 (Brown & Shafer, 2004).

Conclusions

On a global basis, grazing lands sequester substantial amounts of SOC annually. With improved management, the potential to sequester C on many of these lands can be greatly enhanced. Improved soil C sequestration on grasslands is an important strategy to assist in mitigating the greenhouse gas effect. Policies and programmes that encourage the conservation of current grazing lands and conversion of marginally productive croplands to perennial vegetation are critical to the implementation of strategies to sequester soil C. Additionally, efforts to increase SOC sequestration in grasslands worldwide will have important co-benefits to the environment.

References

Abril, A., & E.H. Bucher (2001). Overgrazing and soil carbon dynamics in the western Chaco of Argentina. *Applied Soil Ecology*, 16, 243-249.

Bauer, A., C.V. Cole & A.L. Black (1987). Soil property comparisons in virgin grazing lands between grazed and nongrazed management systems. *Soil Science Society of America Journal*, 51, 176-182.

Brown, J.R. & S. Shafer (2004). Mitigating global climate change through terrestrial carbon sequestration. In: Proceedings Carbon Sequestration: science, policy and marketing in Wyoming, June 22-23, Casper, WY, Wyoming Carbon Sequestration Advisory Committee, Cheyenne, WY, (CD Power Point Proceedings).

Conant, R.T., K. Paustian & E.T. Elliott (2001). Grazing land management and conversion into grazing land: effects on soil carbon. *Ecological Application*, 11, 343-355.

Derner, J.D., D.D. Briske & T.W. Boutton (1997). Does grazing mediate soil carbon and nitrogen accumulation beneath C4 perennial grasses along an environmental gradient? *Plant and Soil*, 191, 147-156.

FAO (2004). FAO Statistical Databases; Agriculture. <http://apps.fao.org/default.jsp>

Follett, R.F., J.M. Kimble & R. Lal (2001a). The potential of U.S. grazing lands to sequester soil carbon. In: R.F. Follett, J.M. Kimble & R. Lal (eds.) The potential of U.S. Grazing lands to sequester carbon and mitigate the greenhouse effect. Lewis Publishers, Boca Raton, FL, 401-430.

Follett, R.F., J.M. Kimble, S. Leavitt & E. Pruessner (2004). The potential use of soil C isotope analyses to evaluate paleoclimate. *Soil Science*, 169, 471-488.

Follett, R.F., S.E. Samson-Liebig, J.M. Kimble, E.G. Pruessner & S.W. Waltman (2001b). Carbon sequestration under the conservation reserve program in the historic grazing land soils of the United States of America. In: R. Lal (ed.) Soil carbon sequestration and the greenhouse effect. *Soil Science Society of America*, Madison, WI, 57, 27–40.

Follett, R.F.& S.R. Wilkinson (1995). Nutrient management of forages. In R.F. Barnes, D.A. Miller & C.J. Nelson (eds.) Forages: the science of grazing land agriculture. Vol II, IA State University Press, Ames, IA, 55-82.

Frank, A.B. (2004). Six years of CO2 flux measurements for moderately grazed mixed-grass prairie. *Environmental Management,* 33 (Supplement), (In press).

Frank, A.B., D.L. Tanaka, L. Hofmann & R.F. Follett (1995). Soil carbon and nitrogen of Northern Great Plains grazing lands as influenced by long-term grazing. *Journal of Range Management*, 48, 470-474.

Franzluebbers, A.J., J.A. Stuedeman & H.H. Schomberg (2000a). Soil organic C and N pools under long-term pasture management in the Southern Piedmont, USA. *Soil Biology Biochemistry*, 32, 469-478.

Franzluebbers, A.J., J.A. Stuedeman & H.H. Schomberg (2000b). Spatial distribution of soil carbon and nitrogen pools under grazed tall fescue. *Soil Science Society of America Journal*, 64, 635-639.

Fuhlendorf, S.D., H. Zhang, T.R. Tunnell, D.M. Engle & A.F. Cross (2002). Effects of grazing on restoration of southern mixed prairie soils. *Restoration Ecology*, 10, 401-407.

Gebhart, D.L., H.B. Johnson, H.S. Mayeux & H.W. Polley (1994). The CRP increases soil organic carbon. *Journal of Soil and Water Conservation,* 49, 374-377.

Haynes, R.J. & P.H. Williams (1992). Accumulations of soil organic matter and the forms, mineralisation potential and plant-availability of accumulated organic sulphur: effects of pasture improvement and intensive cultivation. *Soil Biology and Biochemistry*, 24, 209-217.

Henderson, D.C., B.H. Ellert & M.A. Naeth (2004). Grazing and soil carbon along a gradient of Alberta rangelands. *Journal of Range Management*, 57, 402-410.

Hibbard, K.A., S. Archer, D.S. Schimel & D.W. Valentine (2001). Biogeochemical changes accompanying woody plant encroachment in a subtropical savannah. *Ecology*, 82, 1999-2011.

Kephart, K.D., C.P. West & D.A. Wedin (1995). Grazing land ecosystems and their improvement. In: R.F. Barnes, D.A. Miller & C.J. Nelson (eds.) Forages (V 1), 5th Edition, Iowa State University Press, Ames, IA, 141-153.

Kreileman, E. van, J. Woerden & J. Bakkes (1998). RIVM environmental research 1998 World Regions and Subregions. National Institute of Public Health and the Environment. Bilthoven, The Netherlands. CIM Report no MO25/98, 20p.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304, 1623-1627.

Lal, R., R.F. Follett & J.M. Kimble (2003). Achieving soil carbon sequestration in the United States: a challenge to policy makers. *Soil Science*, 168, 827-845.

LeCain, D.R., J.A. Morgan, G.E. Schuman, J.D. Reeder & R.H. Hart (2000). Carbon exchange of grazed and ungrazed pastures of a mixed grass prairie. *Journal of Range Management,* 53, 199-206.

Liao, J.D. (004). Woodland development and soil carbon and nitrogen dynamics and storage in a subtropical savanna ecosystem. Ph.D. Dissertation, Texas A&M University, College Station, TX.

Manley, J.T., G.E. Schuman, J.D, Reeder & R.H. Hart (1995). Rangeland soil carbon and nitrogen responses to grazing. *Journal of Soil and Water Conservation*, 50, 294-298.

Mortenson, M.C., G.E. Schuman & L.J. Ingram (2004). Carbon sequestration in rangelands interseeded with yellow-flowering alfalfa (Medicago sativa ssp. falcata). *Environmental Management*, 33 (Supplement), S475-S481.

Nyborg, M., E.D. Solberg & S.S. Malhi (1994). Soil C content under bromegrass increased by N and S fertilizer applications. In: Proceedings 31st Annual Alberta Soil Science Workshop, Edmonton, Alberta, 325-328.

Olsson, L. & J. Ardö (2002). Soil carbon sequestration in degraded semiarid agro-ecosystems – perils and potentials. *Ambio*, 31, 471-477.

Potter, K.N., J.A. Daniel, W. Altom & H.A. Torbert (2001). Stocking rate effect on soil carbon and nitrogen in degraded soils. *Journal of Soil Water Conservation*, 56, 233-236.

Potter, K.N., H.A. Torbert, H.B. Johnson & C.R. Tischler (1999). Carbon storage after long-term grass establishment on degraded soils. *Soil Science*, 164, 718-725.

Qian, Y.L. & R.F. Follett (2002). Assessing carbon sequestration in turf grass soil using long-term soil testing data. *Agronomy Journal*, 94, 930-935.

Reeder, J.D. & G.E. Schuman (2002). Influence of livestock grazing on C sequestration in semi-arid mixed-grass and short-grass rangelands. *Environmental Pollution*, 116, 457-463.

Rice, C.W. (2000). Soil organic C and N in rangeland soils under elevated CO2 and land management. In: Proceedings, advances in terrestrial ecosystem carbon inventory, measurements, and monitoring, October 3-5, 2000. USDA-ARS, USDA-FS, USDA-NRCS, U.S. Dept of Energy, NASA, and National Council for Air and Stream Improvement. Raleigh, NC, p 83pp.

Ridley, A.M., W.J. Slattery, K.R. Helyar & A. Cowling (1990). The importance of the carbon cycle to acidification of a grazed annual pasture. *Australian Journal of Experimental Agricultural Research*, 30, 529-537.

Sampson, R.N. & R.J. Scholes. (2000). Additional human-induced activities-article 3.4. In: R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo & D.J. Dokken (eds.) Land use, land-use change and forestry. A Special Report of the IPCC, Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 183-281.

Schnabel, R.R., A.J. Franzluebbers, W.L. Stout, M.A. Sanderson & J.A. Stuedeman (2001). Effects of pasture management practices. In: R.F. Follett, J.M. Kimble & R. Lal (eds.) The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect. Lewis Publishing, Boca Raton, FL, 291-322.

Schuman, G.E. & J.D. Derner (2004). Carbon sequestration by rangelands: management effects and potential. In: Proceedings, Western Regional Cooperative Soil Survey Conference, June 13-17, 2004, Jackson, WY. Natural Resources Conservation Service, USDA, Casper, WY, (in press).

Schuman, G.E., J.D. Reeder, J.T. Manley, R.H. Hart & W.A. Manley (1999). Impact of grazing management on the carbon and nitrogen balance of a mixed-grass rangeland. *Ecological Applications,* 9, 65-71.

Smoliak, S., J.F. Dormaar & A. Johnston (1972). Long-term grazing effects on *Stipa-Bouteloua* prairie soils. *Journal of Range Management*, 25, 246-250.

Sperow, M., M. Eve & K. Paustian (2003). Potential soil C sequestration on US agricultural soils. *Climatic Change,* 57, 319-339.

Stahl, P.D., J.D. Anderson, L.J. Ingram, G.E. Schuman & D.L. Mummey (2003). Accumulation of organic carbon in reclaimed coal mine soils of Wyoming. In: R.I. Barnhisel (ed.) Working together for innovative reclamation, 20th Annual Meeting, American Society of Mining and Reclamation, June 3-6, Billings, MT. American Society of Mining and Reclamation, Lexington, KY, 1206-1215.

Stout, W.L. (1992). Water-use efficiency of grasses as affected by soil, nitrogen, and temperature. *Soil Science Society of America Journal*, 56, 897-902.

Stout, W.L. &. G.A. Jung (1995). Effects of soil and environment on biomass accumulation of switchgrass. *Agronomy Journal*, 87, 663-669.

Stout, W.L. & G.A. Jung (1992). Influences of soil environment on biomass and nitrogen accumulation rates of orchard grass. *Agronomy Journal*, 84, 1011-1019.

Teague, W.R., J.K. Foy, B.T. Cross & S.L. Dowhower (1999). Soil carbon and nitrogen changes following root-plowing of rangeland. *Journal of Range Management,* 52, 666-670.

Van den Pol-van Dasselaar, A., & E.A. Lantinga (1995). Modelling the carbon cycle of grazing lands in the Netherlands under various management strategies and environmental conditions. *Netherlands Journal of Agricultural Science*, 43, 183-194.

Vicente-Chandler, J., R. Caro-Costas, F. Abruna & S. Silva (1983). Produccion y utilizacion intensiva de las forrajeras en Puerto Rico (Production and utilization of intensively managed forages in Puerto Rico). Universidad de Puerto Rico. Estacion Experimental Agricola Boletin, 271, 226pp.

Vicente-Chandler, J., R. Caro-Costas, R.W. Pearson, F. Abruna, J. Figarella & S. Silva (1964). The intensive management of tropical forages in Puerto Rico. University of Puerto Rico. Agriculture Experiment Station Bulletin 187, 152pp.

Weden, D.A. & D. Tilman (1996). Influence of nitrogen loading and species composition on the carbon balance of grazing lands. *Science*, 274, 1720-1723.

West, C.P., A.P. Mallarino, W.F. Wedin & D.B. Marx (1989). Spatial variability of soil chemical properties in grazed pasture. *Soil Science Society of America Journal*, 53, 784-789.