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Carbon sequestration in grassland systems

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Abstract
Globally soils contain around twice the amount of carbon in the atmosphere and thrice in vegetations. Therefore, soil is both 'a source and a sink' for greenhouse gases and balance between the functions is very delicate. The gases move continuously from one pool to another maintaining balance in different pools of the ecosystem. Appropriate management of soil offers to the potential to provide solutions for each of the challenges related to food security and climate change. The estimated carbon sequestration potential of world soils lies between 0.4 to 1.2 Gt per year which includes 0.01-0.30 Gt per year from grasslands. Carbon sequestration can be enhanced in grasslands through grazing management, sowing favorable forage species, fertilizer application and irrigation, restoration of degraded grasslands etc. However, there are certain limitations that hinder in adopting the practices for enhancing carbon sequestration in grasslands. The limitations include continuous degradation of grasslands, changing climate, paucity of information on carbon stock of grasslands from developing countries, disagreement on systems for documenting carbon stock changes over a period of time, hindrance in policy implementations etc.

Keywords: Carbon sequestration, Grasslands, Management practices, Limitations

Grasslands cover around 3.5 billion ha area, representing 26 percent of the world land area and 70 percent of the world agricultural area, and containing about 20 percent of the world's soil carbon stocks (Conant, 2010). Many countries are rich in grassland resources (Table 1). People depend on these grassland resources for food and forage production. Around 20 percent of the world's native grasslands have been converted to cultivated crops but still a significant portion of the milk (27%) and meat (23%) produced in the world comes from grasslands. In fact, the livestock industry is primarily based on such grasslands and provides livelihoods for about 1 billion of the world's poorest people and one-third of global prot-ein intake (FAO, 2006). In some developing countries, the livestock sector even accounts for 50-80 percent of GDP (World Bank, 2007). But these grasslands is now under pressure to produce more and more livestock by grazing more intensively, specially in rangelands of developing countries, which are vulnerable to climate change and are expected nonetheless to supply a substantial quantity of the meat and milk in years ahead. As a result of past practices, 7.5 percent of the world's grasslands have already been degraded due to overgrazing. Cultivation of native grasslands contributes to the transfer of about 0.8 Mg of soil C to the atmosphere annually. Soil organic matters lost due to conversion of native grasslands to cultivation are also extensive. Removal of large amounts of aboveground biomass, continuous heavy stocking rates and poor grazing management practices are important human-controlled factors that influence grassland production and have led to the depletion of soil carbon stocks. However, good grassland management can potentially reverse historical soil carbon losses and sequester substantial amounts of carbon in soils. Studies have indicated that improved grazing management can lead to greater forage production, more efficient use of land resources, and enhanced profitability and rehabilitation of degraded lands.

Global carbon cycle and grasslands

Carbon dioxide (CO_2) is one of many greenhouse gases that keep warm the atmosphere by trapping heat radiating from earth. This trapped heat is called the greenhouse effect and without it the earth would have been about 33 ^{0}C colder. In the recent past there is increase in concentration of carbon dioxide as a result of anthropogenic activities. As we burn more and more fossil fuels to power our vehicles, keep our industry running and make our homes more comfortable, we are increasing concentrations of greenhouse gases in the atmosphere. At present, human activity adds about seven billion tones of carbon dioxide into the air every year. Indeed, the global carbon cycle is closely linked to the greenhouse effect. Carbon moves continuously among air, plants, and soils and changes to any of these three components invariably affects the other components. Through the process of photosynthesis, plants capture atmospheric carbon dioxide and store the carbon in their living tissue, both above and below the ground. Some of this organic carbon becomes part of the soil as plant parts die and decompose, and some is lost back to the atmosphere as gaseous carbon emissions through plant respiration and decomposition. Herbaceous grassland plants contribute to grassland carbon stores primarily by the growth and sloughing of roots, a cyclical process in the case of perennial species and especially when grazed. When such a plant is pruned back, as with grazing, a roughly equivalent amount of roots dies off (adding carbon to the soil) because the remaining top-growth can no longer photosynthesize enough food to feed the plant's entire root system. If given adequate rest from grazing, both roots and top-growth recover and the cycle begins again. With good grazing management, perennial plants can live and reproduce for many years with an ongoing cycle of pruning, root-sloughing, and regeneration, contributing more and more carbon to the soil indefinitely.

Globally, there is about two times as much carbon in soil organic matter (SOM) than there is in the atmosphere and as a result, a relatively small shift in soil organic matter can have a large impact on carbon dioxide in the air (Janzen *et al.,* 2002). To stop rising concentrations of carbon dioxide in the atmosphere, countries around the world are actively seeking means and ways to increase carbon storage on land. The large amount of land area covered by grasslands as well as the relatively unexplored potential for grasslands soils to store carbon has incre-

Table 1. Countries rich in grassland resources

Rank	Country	Region	Total land area (km^2)	Total grassland area (km^2)	Grassland area (%)
1	Australia	Oceania	7,704,716	6,576,417	85.36
2	Russian federation	Europe	16,851,600	6,256,518	37.13
3	China	Asia	9,336,856	3,919,452	41.98
4	United States	North America	9,453,224	3,384,086	35.80
5	Canada	North America	9,908,913	3,167,559	31.97
6	Kazakhastan	Asia	2,715,317	1,670,581	61.52
7	Brazil	South America	8,506,268	1,528,305	17.97
8	Argentina	South America	2,781,237	1,462,884	52.60
9	Mongolia	Asia	1,558,853	1,307,746	83.89
10	Sudan	Sub-Saharan Africa	2,490,706	1,292,163	51.88
11	Angola	Sub-Saharan Africa	1,252,365	1,000,087	79.86
12	Mexico	C. America & Crib.	1,962,065	944,751	48.15
13	South Africa	Sub-Saharan Africa	1,223,084	898,712	73.47
14	Ethiopia	Sub-Saharan Africa	1,132,213	824,795	72.85
15	Congo Dem. Rep.	Sub-Saharan Africa	2,336,888	807,310	34.55
16	Iran	Middle East & N. Africa	1,624,255	748,429	46.08
17	Nigeria	Sub-Saharan Africa	912,351	700,158	76.74
18	Namibia	Sub-Saharan Africa	825,606	665,697	80.63
19	Tanzania, United Republic	Sub-Saharan Africa	945,226	658,563	69.67
20	Mozambique	Sub-Saharan Africa	788,938	643,632	81.58
21	Chad	Sub-Saharan Africa	1,167,685	632,071	54.13
22	Mali	Sub-Saharan Africa	1,256,296	567,140	45.14
23	Central African Republic	Sub-Saharan Africa	621,192	554,103	89.20
24	Somalia	Sub-Saharan Africa	639,004	553,963	89.69
25	India	Asia	3,090,846	535,441	17.32
26	Zambia	Sub-Saharan Africa	754,676	526,843	69.81
27	Botswana	Sub-Saharan Africa	579,948	508,920	87.75
28	Saudi Arabia	Middle East & N. Africa	1,958,974	502,935	25.67

Source: Murphy-Bokern (2009)

-ased interest in the carbon cycles of these ecosystems. Areas where more carbon is absorbed than given off are referred to as carbon sinks and include areas such as native grasslands, forests and agro-ecosystems. In global context, grasslands store around 34% of the global terrestrial stock of carbon while forests store around 39% and agro-ecosystems around 17 percent (World Resources Institute, 2000). Unlike forests where the vegetation is the primary source of carbon storage, most of the grassland carbon is stored in the soil.

Carbon in grasslands

Tropical and temperate natural grasslands play a significant role in the global carbon cycle but poorly recognized. Grassland soil carbon stocks amount to at least 10% of the global total, but other sources indicated it is up to 30% of world soil carbon. Comparisons of SOM stocks between biomes and different studies are complicated by divergent definitions and procedures, but at least it can be said that grassland soils represent a significant carbon pool, of the order of 200-300 Pg (Scurlock and Hall, 1998). In fact, grassland ecosystems are far from uniform, ranging from the natural savannas of Africa to the prairies and steppes of North America and Russia, from the derived savannas found on many continents to the sown pastures of Europe and Latin America.

One of the reasons for the intensive use of grasslands is the high natural soil fertility. Grasslands characteristically have high inherent SOM content, averaging 333 Mg/ha. SOM, an important source of plant nutrients, influences the fate of organic residues and inorganic fertilizers, increases soil aggregation, which can limit soil erosion, and also increases cat ion exchange and water holding capacities. It is a key regulator of grassland ecosystem processes. Thus, a prime underlying goal of sustainable management of grassland ecosystems is to maintain high levels of SOM and soil carbon stocks. Primary production in overgrazed grasslands can decrease if herbivory reduces plant growth or regeneration capacity, vegetation density and community biomass, or if community composition changes. If carbon inputs to the soil in these systems decrease because of decreased net primary production or direct carbon removal by livestock, soil carbon stocks will decline. Similar to carbon sequestration in forests or agricultural land, sequestration in grassland systems primarily, but not entirely in the soils, is brought about by increasing carbon inputs. It is widely accepted that continuous excessive grazing is detrimental to plant communities and soil carbon stocks. When management practices that deplete soil carbon stocks are reversed, grassland ecosystem carbon stocks can be rebuilt, sequestering atmospheric CO_2.

Grasslands as carbon sinks

An estimate has indicated that globally, 0.2 - 0.8 Gt CO_2 per year can be sequestered in grassland soils by 2030. Although both fertilization and fire management can contribute to carbon sequestration, most of the potential regression equation developed between TOC and biomass production of twelve legumes showed significantly high R^2 (0.61) value except *Alysicarpus ragouts* and *Clitoral ternate* (Rai *et al.*, 2013).

Adoption of agroforestry practices: Agroforestry like silvipasture system enhances carbon uptake by lengthening the growing season, expanding the niches from which water and soil nutrients are drawn and, in the case of nitrogen (N)-fixing species, enhancing soil fertility. When silvipasture systems are introduced in suitable locations, carbon is sequestered in the tree biomass and tends to be sequestered in the soil as well (Table 3). Improved management in existing agroforestry systems can sequester 0.012 Tg C per year, while conversion of 630 million ha of unproductive or degraded croplands and grasslands to agroforestry can sequester as much as 0.59 Tg C annually by 2040. Indeed, the C sequestration potential of agroforestry system has been found to vary between 12 and 228 Mg/ha with a median value of 95 Mg/ha. Agro forestry systems are believed to have a higher potential to sequester C than pastures or field crops (Kirby and Potvin, 2007). This hypothesis is based on the assumption that introduction of trees in croplands and pasture would result in greater net aboveground as well as below ground C sequestration (Haile *et al.,* 2008; Singh and Gill, 2014). Abundant litters and/or pruning biomass returned to the soil combined with the decay of roots, contribute to the improvement of soil physical and chemical properties. The land-use systems ranked in terms of their SOC content are in the order of forests>agro forestry>tree plantations> arable crops.

Restoration of degraded lands and introduction of grasses on arable lands: Restoring degraded lands enhances production in areas with low herbage productivity, increasing carbon inputs and sequestering carbon. It is now well documented that practices like silvipastures, hortipastures, improved grazing management etc could lead to greater forage production, more efficient use of land resources, and enhanced sequestration in non-degraded grasslands is due to changes in grazing management practices. Estimated rates of carbon sequestration per unit are lower than those for sequestration on agricultural land, but sequestration potential is comparable to that of croplands because grasslands cover such a large portion of the earth's surface. Management practices used to increase livestock forage production also have the potential to augment soil carbon stocks, thus sequestering atmospheric carbon in soils. Methods of improved management practices include intensive grazing management, fertilization, irrigation, and sowing of favourable forage grasses and legumes. Improved grazing management (management that increases production) leads to an increase of soil carbon stocks by an average of 0.35 Mg C /ha/yr.

Grazing management: It is now proven fact that well managed grazing stimulates growth of herbaceous species and improves nutrient cycling in grassland ecosystems. Increased early season photosynthesis (as measured by chamber CO_2 exchange rates) was observed on grazed mixed-grass prairie compared to ungrazed prairie/exclosures (LeCain *et al*., 2000). Similarly it was reported that grazing stimulates aboveground production (McNaughton *et al.,* 1996) and increases tillering and rhizome production (Schuman *et al.,* 1990). Besides, grazing may stimulate root respiration and root exudation rates (Dyer and Bokhari, 1976). Livestock defecation and urination also significantly affect nutrient cycling and relocation in grazing systems. All of these factors might have contributed to the observed increases in soil C storage. The grazing process also affects the rate of turnover/decomposition of the aboveground component of the plant community (litter, standing dead). Under light and heavy grazing shoot turnover was found to be 36 and 39% compared to 28% in ungrazed exclosures. It was concluded that animal traffic might enhance the physical breakdown, soil incorporation and rate of decomposition of litter and standing dead plant material (Schuman *et al.,* 2002). Again grazing management can lead to decreased carbon removal if grazing intensities are reduced or if grazing is deferred while forage species are most actively growing. Sustainable grazing management can thus increase carbon inputs and carbon stocks without necessarily reducing forage production. Grazing management can also be used to restore productive forage species, further augmenting carbon inputs and soil carbon stocks.

Fertilizer application and irrigation: In many cases grasslands were found to be deficient in N and they have exhibited increased production and increased water-use-efficiency in response to N fertilizations. Fertilizer application stimulated litter production, thereby enhancing soil C storage. N fertilizer application increased plant production of the tall grass prairie and resulted in an increase in soil C of 1.6 Mg/ha (Rice, 2000). Application of 40 kg N/ha caused significant increase in dry forage yield and total organic carbon (TOC) content of the soil in natural pasture (Rai *et al*., 2013). The rate of TOC buildup was 1.5 times more than the natural grassland (0.74 g/kg/yr). Application of other nutrients, where they were deficient, also enhanced organic C storage (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 (Schuman *et al.,* 2002). Similarly, application of water/irrigation can enhance water and nitrogen balances leading to increase in plant productivity and carbon inputs.

Fire management: In some grassland, fire management also influence the amount of C stored in biomass by altering the density or encroachment of woody species. Burning of biomass produces charcoal, a form of C very resistant to decomposition, which can account for a significant portion of the C stored in some grassland soils. Annual burning and grazing on the tall grass prairie were found to increase in soil C storage of 2.2 Mg/ha after 10 years, which accounted for an increase of 0.22 Mg/ha/year (Rice, 2000).

Sowing of favourable forage species: Introduction or promoting improved and favourable forage species that are better adapted to local climate, more resilient to grazing, more resistant to drought and able to enhance soil fertility can lead to increased biomass production. Enhancing production ultimately results in greater carbon inputs and carbon sequestration. It was observed that introduction of *Macroptilium lathyroides* in natural grassland resulted in 1.29 times increase in TOC as compared to natural grassland. Other legumes also showed increased mixed biomass production and soil TOC (Table 2). Maximum increase in TOC and soil organic carbon (SOC) buildup rate was observed with *micropitilum lathyroildes* (42%) followed by *Stylosanthes guianensis*. Except *Alysicarpus ragouts* and *Clitoris tenanted* the rate of TOC buildup was higher in legume incorporated grassland than the natural grassland. The

Table 2. Effect of range legumes on forage yield of natural grassland and organic carbon in the soil

Treatments	Forage DM yield (Mg/ha)	TOC (g/kg)	SOC buildup rate (g/kg/yr)
Natural grassland	3.3	7.78	0.74
Alysicarapus rugosus	4.2	7.55	0.67
Atylosia scarabaeoides	4.1	9.22	1.22
Clitoria ternatea	4.4	7.47	0.64
Dolichos lablab	4.7	10.07	1.51
Desmodium tortusum	4.2	9.72	1.39
Glycine javanica	3.8	8.58	1.01
Macroptilium atropurpureum	4.1	7.99	0.81
Macroptilium lathyroides	4.9	11.05	1.83
Mimosa invisa	3.7	8.91	1.12
Stizolobium deeringianum	4.0	8.10	0.85
Stylosanthes guianensis	4.2	10.53	1.66
Stylosanthes humilis	4.0	8.22	0.89
Vigna luteola	4.2	9.15	1.20

Source: Rai *et al.*(2013)

profitability and rehabilitation of degraded lands and restoration of ecosystem services. Silvipasture system had a great role in rehabilitating the degraded land. Eight different tree species were tested as component of *Cenchrus ciliaris* based silvipasture for their relative efficacy on herbage production against *Cenchrus ciliaris* as pasture (Table 4). Photosyntnthetically active radiation (PAR) reaching to the ground affected the performance of the understory vegetation under different tree species. Relative radiation infiltration through tree species varied between 58-78%, lowest being in Acacia nilotica and highest in Eucalyptus sp. Variation in litters fall and biomass production under different trees affected the TOC content of the surface soil. In the same period *Leucaena leucocephala* caused 3.4 times increase in the TOC over the initial values. TOC content was maximum in *Leucaena leucocephala* followed by *Albizzia lebbeck*, *Dichrostachys mutants, Albizzia proceura* and others.

It has been observed that different arable land-use systems result in very rapid declines in SOM. Much of this loss in soil organic carbon can be attributed to reduced inputs of organic matter, increased decomposability of crop residues, and tillage effects that decrease the amount of physical protection to decomposition. Including grass in the rotation cycle on arable lands can increase production return organic matter (when grazed as a forage crop), and reduce disturbance to the soil through tillage. Thus, integrating grasses into crop rotations can enhance carbon inputs and reduce decomposition losses of carbon, each of which leads to carbon sequestration (Conant, 2010).

Based on present management practices majority of the grasslands in temperate regions are considered as C sinks (Abberton *et al.*, 2010; Acharya *et al.*, 2012). It was observed that the land-use change from arable cropping to grassland results in an increase of soil C of 30 g C/m^2/year. Direct measurements of soil C indicated a C sequestration of 45–80 g C/m^2/year. In France, meta analysis has shown that on average, for a 0–30 cm soil depth, C sequestration reached 44 g C/m^2/year over 20 years. This is approximately half the rate (95 g C/m^2/s/year) at which C is lost over a 20–year period following conversion of permanent grassland to an annual cropland (Soussana *et al.,* 2004). Temperate pastures in the northeast USA are highly productive, they can potentially act as significant C sinks. However, these pastures are subjected to relatively high biomass removal as hay or through consumption by grazing animals. Consequently, for the first eight years after conversion from ploughed fields to pastures, they were a small net sink for C at 19 g C/m^2/year but when biomass removal and manure deposition were included to calculate net biome productivity, the pasture was a net source of 81 g C/m^2/year. It was concluded that heavy use of biomass produced on grasslands prevents them from becoming C sinks. C sequestration potential for managed grasslands in USA was found to be 10–90 g C/m^2/year depending on the level of change. Based on the Kyoto Protocol on Climate Change for Europe, C sequestrations were 52 g C/m^2/year for established grassland and 144 g C/m^2/year for conversion of arable land to grassland. Country estimates varied from a source of 4.5 g C/m^2/year for Portugal to sequestration of 40.1 g C/m^2/year for Switzerland. However, estimates based on the full GHG balance for grasslands across Europe indicated that most grassland areas are net sources for GHGs in terms of their total global warming potential because the beneficial effect of sequestering C in soils is outweighed by the emissions of N_2O from soils and CH_4 from livestock (Levy *et al.,* 2007).

Limitations of carbon sequestration in grasslands

All ecosystems namely forest ecosystem, agro-ecosystem, grassland ecosystem, etc. take up atmospheric CO_2 and mineral nutrients and transform them into organic products (Conant, 2010). In grasslands, carbon assimilation is directed towards the production of fibre and forage by manipulating species composition and growing conditions. These ecosystems are a major source and sink for the three main biogenic greenhouse gases (GHG); CO_2, nitrous oxide (N_2O) and methane (CH_4). In undisturbed ecosystems, the carbon balance tends to be positive: carbon uptake through photosynthesis exceeds losses from respiration. Thus the basic processes governing the carbon balance of grasslands are similar to those of other ecosystems: the photosynthetic uptake and assimilation of CO_2 into organic compounds and the release of gaseous carbon through respiration (primarily CO_2 but also CH_4). However, biomass in grassland systems, being predominantly herbaceous (i.e. non- woody), is a small, transient carbon pool (compared to forest) and hence soils constitute the dominant carbon stock. Grassland systems thus can be productive ecosystems, but have certain limitations as discussed below (Mengistu and Mekuriaw, 2014):

Changing climate: Grasslands are highly vulnerable to climate change. Primary production in natural grasslands is relatively low, varies considerably from place to place, and is strongly limited by precipitation. Even where rainfall is high (upto 900 mm of precipitation per year), almost all of the precipitation falls during distinct rainy seasons and evapotranspiration demands exceed precipitation during most of the year. Hence, precipitation, and thus production, varies considerably from year to year, with coefficients of variation averaging 33%, and as high as 60% in some of the drier areas. But grassland management practices that sequester carbon tend to make systems more resilient to climate variation and climate change. Increased SOM (and carbon stocks) improves yields, enhances soil fertility, reducing reliance on external nitrogen inputs. Surface cover, mulch and SOM all contribute to a decrease in inter-annual variation in yields; and practices that diversify cropping systems,

Table 3. Soil carbon sequestration in different agroforestry systems

Agro forestry system/species	Age (yr)	Soil C (Mg/ha)	Soil depth (cm)
Agro forestry (*Pseudotsuga menzeiscii* + *Trifolium subterraneum*)	11	0-45	95.89
Agrisilviculture (*Gmelina arborea* + field crops)	5	0-60	27.4
Silvopastoral system: (*Acacia mangium* + *Arachis pintoi*)	10-16	0-100	173
Silvopastoral system: (*Brachiaria brizantha* + *Coradia alliodora* + *Guazuma ulmifolia*)	10-16	0-100	132*
Alley cropping system: *Erythrina poeppigiana* + maize and bean (*Phaseolus vulgaris*)	19	0-40	1.62
Fodder bank (*Gliricidia sepium*, *Pterocarpus lucens* and *P. erinaceus*)	6-9	0-100	33.4
Tree based pastures: slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*)	8-40	0-125	6.9-24.2
Gliricidia sepium + maize (*Zea mays*)	10	0-200	123

*Carbon-sequestration potential, which is based on C-stock estimates; **Source**: Nair *et al.* (2009); Rai *et al.* (2013)

Table 4. Influence of tree species on forage yield, leaf litter and TOC content of soil in *Cenchrus ciliaris* silvipasture

Tree	Dry forage yield (Mg/ha)	Leaf litters (Mg/ha)	TOC (g/kg soil)	Relative increase
Albizzia lebbeck	3.40	5.63	9.31	3.04
Albizzia procera	2.30	4.21	8.37	2.73
Acacia tortilis	0.70	4.36	7.44	2.43
Acacia nilotica	2.20	4.47	7.98	2.61
Leucaena leucocephala	3.20	5.28	10.37	3.39
Dichrostachys nutan	2.00	5.46	9.04	2.96
Hardwikia binata	1.50	5.34	7.18	2.35
Eucalypytus sp.	2.00	3.87	6.91	2.26
Open (without tree)	-	5.95	6.91	2.26
Initial*	-	0.62	3.05	

*Initial vegetation was comprised of *Aristida* sps., *Eromopogon faveolatus* and *Heteropogon contortus*; **Source:** Hazra (1995) such as grass and forage crops in rotation, sequester carbon and enhance yield consistency.

Continuous degradation of grasslands: Grassland degradation is continuously occurring under all climates and farming systems, and is generally related to a mismatch between livestock density and the capacity of the pasture/grassland to be grazed and trampled.

Mismanagement is common. Ideally the land/livestock ratio should becontinuously adjusted to the conditions of the pasture, especially in dry climates where biomass production is erratic, yet such adjustment is rarely practiced. This is particularly the case of arid and semi-arid regions where communal grazing is prevalent. In these areas, increasing population and encroachment of arable farming on grazing lands have severely restricted the mobility and flexibility of the herds, which enabled this adjustment. Grassland degradation results in a series of environment problems, including soil erosion, degradation of vegetation, carbon release from organic matter decomposition, loss of biodiversity owing to habitat changes and impaired water cycles.

***Limited information on carbon stock of grasslands from developing countries*:** There is paucity of information/data from developed countries which limits to the creation of robust accounting systems that offer the same utility for quantifying soil carbon sequestration in developed and developing countries. In fact, systems that integrate measurement and mechanistic modeling require robust sources of data that reflect the range of potential management practices. A variety of efforts are under way across the developed world to build up, test and implement such systems. Lack of accurate information on these aspects can lead to greater uncertainty in estimates of soil carbon stock changes, and ultimately result in climate-driven bias because majority of studies from developed country are related to temperate regions.

Disagreement on systems for documenting carbon stock changes: Soil carbon stocks of an ecosystem vary as a function of soil texture, landscape position, drainage, plant productivity and bulk density, all of which vary spatially, and create heterogeneity that makes it difficult to quantify changes in soil carbon stocks over time. However, methods for analyzing soil carbon concentration of a given sample are well established and easily carried out with high precision and minimal analytical error. During quantifying soil carbon stock over time, sampling error can be large and the cumulative effects of managing small net sinks to mitigate fossil-fuel emissions will have to be understood, analyzed, monitored, and evaluated in the context of larger, highly variable, and uncertain sources and sinks in the natural cycle. Thus, the main challenge in documenting plot-level changes in soil carbon stocks is not in measuring carbon, rather designing an efficient, cost-effective sampling and carbon stock estimation system, which also need to be agreed by different stakeholders.

Policy implementation issues: In spite of win–win situations in which practices that sequester carbon in grasslands also lead to enhanced productivity, policies to encourage adoption of practices that sequester carbon in grasslands lag behind policies for forest and agricultural lands. This is particularly true for practices that promote increased primary productivity or livestock production and practices that arrest grassland degradation. Reducing emissions from grassland is not only likely to pay dividends in maintaining carbon stocks, but also in sustaining the livelihoods of people making a living from grasslands. Again smallholder households from developing countries represent a serious limitation for documenting carbon sequestration from grasslands. In many countries pastoralists also occupy substantial portions of the land area with the potential to sequester carbon in grasslands. However, pastoralists are often socially marginalized and with insecure land tenure rights, making it very difficult for participation in carbon markets. Moreover, the strength and ability of government institutions required to implement such schemes is often insufficient in the countries and areas where they are most needed.

Conclusion

The rates of carbon sequestration and soil organic carbon (SOC) values were found to vary among the grassland systems, but it is understandable that grassland systems provide valuable carbon storage. Increasing SOC storage through land use changes and land management is a low cost and environmentally beneficial way of sequestering substantial amounts of atmospheric CO_2 and need to be practiced. However, further research is needed across multiple locations addressing key ecological processes and mechanisms to determine the principal drivers affecting C sequestration (Derner and Schuman, 2007). The continued development of sophisticated *in-situ* and laboratory equipment to accurately detect small but ecologically-important changes in soil C and its components will open new horizons for future experimentation and verification of C change due to management options or climatic variances. There is a need to move from the basic approach of soils and soil ecology to a more fundamental and functional understanding of the processes and mechanisms that affect SOC dynamics and how they are influenced by land management, environment and their interaction. Newly emergent fields of soil microbial ecology should provide additional in sight into microbial function and processes that affect C sequestration under normal and the widely fluctuating precipitation patterns found in arid and semi-arid environments. Hence, as better research information becomes available, a more thorough and accurate estimation of C sequestration potential of grasslands can be achieved in near future.

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