Soil Carbon Sequestration in Dryland Agriculture

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1 Introduction

Carbon sequestration is the transfer of CO_2 from atmosphere into the enduring pools and keeping it stable, so that it cannot directly remitted. Hence, the soil carbon (C) sequestration is the enhancement of soil organic carbon (SOC), and soil inorganic carbon (SIC) pools by wisely land usage and suitable management techniques. The well-managed ecosystems have the possible soil sink capability of almost equals to the collective historic C loss projected at 55–78 Gt (Lal 2004a). The achievable soil C sink capability is only about 50–66 % of the total possible volume. This strategy is quite cost-effective and eco-friendly. The areas where proportion of total annual precipitation to the potential evapotranspiration (PET), the aridity index (AI), ranges from 0.05 to 0.65 are called as drylands, and consist of dry sub-humid areas from 0.50 to 0.65, semi-arid from 0.20 to 0.50, arid from 0.05 to 0.20, and hyper-arid with <0.05 AI, covering 9.9, 17.7, 12.0 and 7.5 % of the world's total land area, respectively (Reynolds and Smith 2002). Drylands cover approximately 6.15 billion hectares, primarily in the Southwestern and Northern Africa, Central and Southwestern Asia, Northwestern Pakistan and India, Australia, Southwestern Mexico and United States (Noin and Clarke 1997; Hillel and Rosenzweig 2002).

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Globally, drylands hold 241 Pg of SOC (Eswaran et al. 2000), almost 40 times higher C as compared to the addition into atmosphere by anthropogenic actions, during 1990s, which was 6.3 Pg C year^{-1} (Schimel et al. 2001). Drylands contain higher levels of SIC as compared to the SOC (Eswaran et al. 2000).

In drylands, mutual management of SIC and SOC can play a key role in the reduction of CO_2 concentration in the atmosphere (Lal 2002b). Global C cycle is strongly affected by drylands due to vast areas and significance of these soil C pools. On the other hand, in these areas, desertification and land degradation are prevalent, which often consequence in CO_2 emission into the atmosphere (Lal 2004a). The historic C loss from the ecosystem was projected due to losses from vegetation/biotic pool (10–15 Pg) and by desertification (9–14 Pg of SOC pools) (Lal et al. 1999). Likewise, global C (13–24 Pg) has been lost due to desertification of drylands and grasslands (Ojima et al. 1995). Whereas all the ecosystem C loss estimates through desertification are hypothetical, the figures are higher at about 20–30 Pg (Lal 2004a). If two third from this would be sequestered by controlling desertification, and with the implementation of recommended soil management techniques and land use practices, in 50 years this amount would be at 12–20 Pg (Cole et al. 1997). Technical options vary among diverse soil types and systems of land utilization (Hinman and Hinman 1992).

Although some studies have been conducted on C sequestration in dry lands (Lal 2002b), however, these were conducted on different and individual aspects e.g., C sequestration, effect of climate change, and biophysical aspects etc., This chapter describes the potential of soil C sequestration, mitigation of accelerated greenhouse effect, biophysical aspects of C sequestration, impact of C sequestration on climate change and food security, land use management practices and vegetation management options to combat land degradation in dryland agriculture (Tables 1, 2, and 3).

2 Biophysical Aspects of Carbon Sequestration in Drylands

Grasslands, forests and cultivated lands constitute the major potential C sinks in the drylands. In the followings lines, biophysical aspects of carbon sequestration in drylands are described.

2.1 Grasslands

Natural biome in many drylands developed from grasslands is inadequate for plantation due to low rainfall. Both C sequestration and grassland productivity are thought provoking issues. Because increase in the grassland production, enhances the C sequestration process (Scurlock and Hall 1998), about 70 t ha^{-1} C is stored under grassland areas. However, most of the grasslands are prone to degradation resulting in less sequestration of C. Nonetheless the contribution of grasslands is

Table 1 Improved management systems for soil organic carbon sequestration and soil quality enhancement

Farming system	Improved management	Carbon sequestered	Country/region	References
1. Cropland				
(a) Tillage methods	Time and method of seedbed preparation		Syria	Ryan (1997) and Schomberg and Jones (1999)
(b) Supplemental irrigation	Increasing wheat yield		Syria	Oweis et al. (1998)
(c) N fertilization	50–100 kg N ha^{-1}		Syria	Oweis et al. (1998)
(d) N and P management	Enhancing biomass yield		Sudan, WANA	Matar et al. (1992)
(e) Water/nutrient recycling	Sewage irrigation		Egypt	El-Naim et al. (1987)
(f) Crop rotations	Legume-based system	0.6 t ha^{-1} $year^{-1}$	Syria, Midemanian region	Jenkinson et al. (1999)
2. Grazing/ rangelands				
(a) Soil P level	Residual phosphate and grassland restoration		Syria, WANA	Matar et al. (1992)
(b) Controlled grazing	Extending growing period of shrubs		Egypt	Duivenbooden (1993)
(c) Seed dispersal	Using sheep to disperse leguminous seeds		Syria	Ghassali et al. (1998)
(f) Fodder trees	Nutrient cycling		–	Le Houreou (2000)
(e) Crop/livestock integration	Improving carrying capacity		WANA	Thomson and Bahhady (1995)

higher (1–2 t ha^{-1}) than the croplands (Jenkinson and Rayner 1977). Grasses also sequester more C than leguminous cover crop (Lal et al. 1999). However, in grasslands, controlled grazing led to more C in soil than in conservation tillage systems of the grasslands (Franzluebbers et al. 2000). Plant roots have more potential to add organic matter in soil, because of their physical protection, chemical recalcitrance and physico-chemical complexes of rhizodeposits (Rasse et al. 2005) and as a result more C is stored in the grasslands (Woomer et al. 1994). Garten and Wullschleger (2000) reported that in degraded lands, switch grass (*Panicum virgatum* L.) improved the SOC by 12 %. Through proper grazing management, US rangelands can increase

Table 2 Strategies of soil management in dryland ecosystems for carbon sequestration

Strategy	Practice	Carbon sequestered	Location/Region	References
Erosion control/water conservation	(A) No-till farming		Bushland, TX, USA	Jones et al. (1997)
			Northern CO, USA	Potter et al. (1997)
			Queensland, Australia	Dalal et al. (2000)
		4 Mg ha^{-1}	West Africa Sahel	Bationo et al. (2000)
	(B) Conservation tillage	1.34 % in 0–5 cm	Southern Spain	Murillo et al. (1998)
	(C) Mulching			
	(a) Stone cover		Negev Desert	Lahav and Steinberger (2001)
	(b) Residue mulch		Chihuahuan Desert	Rostagno and Sosebal (2001)
	(c) Mulch		Suriname	Breeman and Protz (1988)
Crop diversification	(a) Rotations		Saudi Arabia, West Asia	Shahin et al. (1998)
			Algeria, North Africa	Arabi and Roose (1989)
	(b) Legumes	0.1–0.3 t ha^{-1} $year^{-1}$	Syria, West Asia	Jenkinson et al. (1999)
		1.37 % in 0–15 cm	Australia	Whitehouse and Littler (1984)
			Northern India	Singh et al. (1996)
		17.3 Mg C ha^{-1}	Argentina	Galantini and Rosell (1997)
Integrated nutrient management and recycling	(a) Manuring		Maiduguri, Nigeria	Aweto and Ayub (1993)
	(b) Organic by-products		Spain	Pascual et al. (1998)
	(c) Soil fauna (enhancing termite activity)		Chihuahuan Desert	Nash and Whitford (1995); Whitford (1996)
	(d) Sewage sludge		Spain	Pedreno et al. (1996)
Water management	(a) Irrigation and conservation tillage		Mexico	Follett et al. (2003)
	(b) Irrigation with sewage		Israel	Hillel (1998)
	(c) Irrigation with silt-laden water		Ningxia, China	Fullen et al. (1995)
	(d) Saline aquaculture		Drylands	Glenn et al. (1993)
	(e) Water harvesting			

Table 3 Strategies of pasture and range land management for soil carbon sequestration

Strategy	Practice	Carbon sequestered	Location/Region	References
Improved species	Sowing legumes	1.6 % in 0–5 cm	Vertisols, Australia	Chan et al. (1997)
			Northern Colorado	Havlin et al. (1990)
			Sadore, Niger	Hiernaux et al. (1999)
	Agroforestry		West African Sahel	Breeman and Kessler (1997)
Fire management	i. Prescribed burning	0.6 t ha^{-1} year^{-1}	Wyoming, USA	Schuman et al. (2002)
	ii. Stocking rate		Negev, Israel	Zaady et al. (2001)
Grazing management	Controlled grazing		Kawas, USA	Rice and Owensby (2001)
Improving grasslands	Integrated management		World's drylands	Conant et al. (2001)
Erosion management	Integrated management		World's drylands	Lal (2001)

soil C storage by 0.1–0.3 t ha^{-1} year^{-1}, and for new grasslands this can rise up to 0.6 t ha^{-1} year^{-1} (Jenkinson et al. 1999; Schuman et al. 2002). The positive effect of grazing has direct impact on species composition and litter accumulation. Therefore, grasslands play an important role in C sequestration, but with careful management. However, semi-arid grasslands are highly sensitive to overgrazing and C loss.

2.2 Forests

Forests are the major sinks for below and above ground C in drylands, because of the availability of various species that establish in the drylands through afforestation (Silver et al. 2000; Kumar et al. 2001; Niles et al. 2002). Mesquite ((*Prosopis glandulosa* Torr.) plantation (N fixing and having deep rooting system), increased the soil C by 2 t ha^{-1} in semi-arid soils (Geesing 2000). In North-West India, planting another type of mesquite (*Prospis juliflora* (Sw.) DC.) in salt affected soils raised the level of organic pool of C from 10 t ha^{-1} to 45 t ha^{-1} in the period of 8 years (Garg 1998). Likewise, in semi-arid climate of India, plantation of jand (*Prosopis cineraria* (L.) Druce) has substantially improved the soil fertility and C sequestration process (Nagarajan and Sundaramoorthy 2000). As natural ecosystems are diverse and multifaceted, therefore sequester less C in to the soils. However, due to increase in biomass levels, the improvements were balanced through loss in the C of soil.

2.3 Fallows

In case of fallows, preservation of vegetation cover is important if there is no cropping. Especially, in drylands where soils are more prone to land degradation. The vegetative cover not only shields the soil but also traps the solar radiations for the fixation of CO_2. In Mediterranean Spain, control and vegetative cover were compared for C storage. Removal of vegetation cover after 4 years of its establishment substantially reduced the C storage up to 35 % than control (Albaladejo et al. 1998). In Nigeria, removal of vegetation cover caused 13.5–25 t ha^{-1} reduction in forest soil C in a period of 7 years, however in 12–13 years of bush free area the C contents were restored (Juo et al. 1995). In North-West USA, decreased fallowing in summer had greater effect on SOC in positive way, as compared to decreased tillage activities (Rasmussen et al. 1998; Miglierina et al. 2000).

Agro-ecosystem projected models showed that reduced summer fallow in wheat-based cropping systems (wheat-wheat-fallow; wheat-fallow), in semi-arid chernozems of western Canada, would reduce C losses by 0.03 t ha^{-1} (Smith et al. 2001a). The importance of fallows for C sequestration depends on addition of amount of organic matter in different cropping systems. If it happens correctly, then presence of fallow lands increases the C stocks in the system.

2.4 Cultivated Lands

Reduction of C stocks in arable land is principally caused by different tillage practices (Pretty et al. 2002). This is due to the tillage implements like, mouldboard plough and disc harrow, which deteriorate the soil structure, and increase the C losses through destruction of soil clumps and increasing demolition through biological activity (decay of residues) (Six et al. 2000). The amount of soil C depends upon the texture of soil. For instance, the coarse texture soils (sandy) are more influenced by the tillage practices than the fine texture soils (clay). It is, therefore, strenuous to figure out the effects of tillage on C stocks in the soil (Buschiazzo et al. 2001). Interestingly, under hot and dry climatic conditions, reduction in tillage was effective to improve soil C stock (Batjes and Sombroek 1997).

An investigation into the tillage-induced CO_2 efflux and C losses from soil indicated that tillage by mouldboard plough buried most of the crop residue and caused the maximum CO_2 efflux (Reicosky 1997). The C discharge (% C in crop residues) by the mouldboard plough and disc harrow was 134 and 70 %, respectively, however disc harrow, chisel plough and no-till had 58, 54 and 27 % C discharge, respectively. This indicated the association of CO_2 release (loss) and the tillage intensity, and demonstrated that ploughing with mouldboard caused maximum loss to soil C. Comparison of conventional disc tillage and no-tillage in Central Texas indicated that constant changes in C sequestration and mineralization had occurred in no-till system (Franzluebbers et al. 1995). Another study, focused on CO_2 emission and soil C stock, indicated that CO_2 release and soil C level from zero or reduced till were more than the conventional tillage system (Costantini et al. 1996).

Adopting no-till approach, decrease in C stock was just 12 % so, no-till system was unable to make dominant decrease in C sinks. Soil surface with crop residues changed the top layer of the soil by modulating the microclimate, which is cool and wet than the conventional tillage (Doran et al. 1998). Decrease in mineralization of the organic portion and organic C, was increased up to 42–50 % in no-till approach than ploughing with the chisel, all this happened due to an increase in the dynamic forms of organic matter under no-till in Argentine rolling pampa. No-till also improved the C distribution in soil profile (Alvarez et al. 1995). A study on total organic carbon (TOC), conducted on sandy clay loam soil, described that in no-till system increase in TOC was dependent on surface layer of soil, so, actual quantity depends on cropping system. For instance, in oat/vetch-maize/cowpea system, about 1.33 t C ha^{-1} $year^{-1}$ was sequestered over a period of 9 years in no-till system. This system also produced a large quantity of crop residues (Bayer et al. 2000). Although in hot environments, the rate of organic matter accumulation is low than the cool environments. However, in sandy soil of northern Syria, under zero-till, there is possibility to make little increase in organic matter of soil (Ryan 1997). In western Nigeria, no-till combined with mulching application increased the soil C from 15 to 32.3 t ha^{-1} over a period of 4 years. However, C losses through conventional cultivation can be minimized with no-till system (Ringius 2002).

The decrease in soil temperature has been linked with crop residues/plant residues on the surface of the soil which may cause delay and/or decrease in the germination. While in dry lands, the temperature is usually above the optimum level, which favors germination, plant growth and establishment (Phillips et al. 1980) under adequate moisture provision. Among the effective implements that can control the weeds, mouldboard plough and disc harrow are the predominant (Reicosky 1995). Usually, no-till systems depend upon extra pesticides and herbicides. However, nitrogen fertilizer application can be problematic under no-tillage systems (Phillips et al. 1980). In less drained soils, denitrification can decrease the rate of evaporation and may increase the risk of nitrogen leaching nitrate. However, like undisturbed soils, native soil nitrogen is unlikely to change from organic to inorganic form (mineralization). All soils are not adaptive for reduced approach of tillage. For instance, in Argentine pampa, some soils may lose more C in no-till approach that is 0.7–1.5 t C ha^{-1} $year^{-1}$, as compared with conventional tillage system (Alvarez et al. 1995), and to get rid from the soil compaction regular ploughing is required (Taboada et al. 1998). While keeping in view the C budget, there is low demand of energy but in reality tillage is very energy demanding approach. In Northern America, after using no-till system, energy inputs used in maize and soybean production were reduced by 7 and 18 %, respectively (Phillips et al. 1980). The capacity of cropping systems to convert water into plant biomass or grain, is the mean of minimizing the use of energy in the form of C and irrigation costs or inputs, while the influence to save energy is often balanced by additional herbicide requirements (Phillips et al. 1980).

The production, and application of herbicides to no-till system of the Great Plains, is approximately 0.02 t C ha^{-1} (Kern and Johnson 1993). In no-till system, the efficacy of C sequestration depends on particular agriculture system, which is being introduced in it. It is not clear either the tillage intensity lessens the balance between C gain and loss (Kern and Johnson 1993). Crop rotation has long term beneficial effects on C sequestration. A comparison of legume-based rotation and continuous maize cultivation indicated that rotation has great effect on soil C than fertilizer application (Gregorich et al. 2001). Crop rotation with legumes increased the organic matter accumulation in the surface layer of soil – the plough layer – and had more biological activities, which indicates that soil plough layer in legume-based rotation have more C stocks (Miglierina et al. 2000). Similarly, in Argentina, legumes and cattle grazing made a beneficial effect (2–4 t ha^{-1}) on SOC (Miglierina et al. 2000). In drylands, legume based rotation plays a vital role in C Sequestration for maintaining soil fertility. For instance, in the drylands of United States, maize/soybean cultivation areas enhanced the soil C sequestration up to 0.01–0.03 Pg C $year^{-1}$. However, the crop rotation could be more valuable and effective in the sequestration process, when is integrated with conservation tillage practices (Drinkwater et al. 1998).

In conclusion, the grasslands have more C sequestration than the croplands but are prone to overgrazing-induced C losses. The forests are the most important sinks for below and above ground C in drylands, due to the presence of diverse species. Vegetation preservation is important in case of fallows. The significance of fallows for C sequestration depends upon organic matter addition by diverse cropping systems. The soil C depends upon soil texture as well; sandy soils are effected more by cultivation than clay in this regard. Therefore, the effects of tillage on C stocks in the soil need to be figured out. Crop rotation has long-term positive effects on C sequestration, and may be more effective through integration with conservation tillage.

3 Impact of Carbon Sequestration on Global Climate Change and Food Security

Carbon sequestration is one of the major drivers of global climate change and the food security. Increase in carbon sequestration can cause substantial reduction in global warming. In the following lines, impact of carbon sequestration on global climate change and food security are discussed.

3.1 Climate Change

The estimation of total soil C sequestration in the world, ranges from a low level 0.4–0.6 Gt C $year^{-1}$ (Sauerbeck 2001) to higher level 0.6–1.2 Gt C $year^{-1}$ (Lal 2003a). This indicates a finite potential with respect to time and capacity.

However, C sequestration in soil provides the time up to the substitutes as fossil fuels come into effect. Impacts of C sequestration on global climate change are discussed below.

3.1.1 Farm Chemicals and Fuel Consumption

Many practices consist of C-based inputs present in N to about 0.86 kg C kg^{-1}, P_2O_5 0.17 kg C kg^{-1}, K_2O 0.12 kg C kg^{-1}, lime 0.36 kg C kg^{-1}, insecticides 4.9 kg C kg^{-1}, herbicides 4.7 kg C kg^{-1}, fungicides 5.2 kg C kg^{-1} (West and Marland 2002), and in groundwater, pumping for irrigation purpose is 150 kg C ha^{-1} (Follett 2001). Tillage practices also discharge C from the soil e.g., plowing with moldboard emits about 15 kg C ha^{-1}, chisel 8 kg C ha^{-1}, light tandem disks about 6 kg C ha^{-1}, sub-soiler 11 kg C ha^{-1}, cultivator 4 kg C ha^{-1}, and rotavator 2 kg ha^{-1} during hoeing (Lal 2004a). So, C release can be decreased by 30–35 kg C ha^{-1} per season if conventional tillage is replaced by no till farming (Lal 2004a). Balanced use of C-based inputs is, however, very important to reduce the C losses.

3.1.2 Nutrition

Carbon is the one of the most important elements that constitutes the living bodies. According to an estimate, for 1 Gt of C sequestration, the world requirement for N, P and K are 80, 20 and 15 million tons, respectively (IFDC 2000). Various C sources including biological nitrogen fixation, reuse of subsoil after recycling, deposits through air, use of waste material from biological resources and from crop residues provide C for sequestration. For instance, one ton cereal residues consist of nutrients as N (12–20 kg), P (1–4 kg), K (7–30 kg), Ca (4–8 kg), and Mg (2–4 kg). Globally, 3 Gt $year^{-1}$ of residues are produced from grain crops, those if used after recycling can be used for fuel, betterment of quality of soil and for sequestration of C. Crop residues are also used for the production of ethanol, and a good source for energy production by burning. These can be utilized for C sequestration to improve the soil quality, and for the production of biofuel. However, the economic assessment of these two competing uses is required in future.

3.1.3 Soil Erosion and Deposition

Soil erosion removes SOC, through the sediments, borne from water and wind. The sediments enriched with SOC are either reallocated over the landscapes, settled down in depressions, and may be passed to the water bodies. Even though a major portion of C, transferred due to erosion, might be covered up and redeployed, the remaining is released to atmosphere by methanogenesis as CH_4 and by mineralization as CO_2 (Smith et al. 2001c). Deposition and burial due to erosion is 0.4–0.6 Gt C $year^{-1}$ than released into atmosphere which is 0.8–1.2 Gt C $year^{-1}$ (Lal 2003b).

The quantification of deposition contrasted with emission of C is of significant concern. Thus an effective soil erosion control is necessary to improve the environmental quality and sustainability of dryland soils.

3.1.4 Exhaustive Farming Practices

In Sub-Saharan Africa, since the mid-1960s, about 40 kg of NPK ha^{-1} of cultivated lands is the yearly nutrients depletion rate, due to subsistence farming (Sanchez 2002). The mining of SOC from the soil for nutrients by decomposition of organic matter has a similar effect on the atmosphere like combustion of fossil fuels. Thus the management practices must be improved rather than degrading the quality of soil, increase crop yield per unit fertilizer and other inputs used rather than decrease or maintain, and increase rather than to deplete the soil fertility and SOC pools.

3.1.5 Societal Value And Hidden Benefits

Soil C commodification is essential for trading C credits, markets have been established for this purpose since 2002, particularly in Europe (Johnson and Heinen 2004). The existing price for SOC is about \$1 t^{-1} of CO_2, which may enhance with the regulation and the emission lid. The credit trading of SOC turn out is a routine part of the capability to quantify temporary ups and downs in the existing SOC pools, the solutions for the mitigation of climate change (Lal et al. 2000). However, the soil C price be essentially based on the both *in-situ* and *ex-situ* social welfares.

3.1.6 Hydrologic and Carbon Cycles

An estimated increase in the production of cereal from 1997 to 2050 is about 56 % (Rosegrant and Cline 2003), which must take place on equal or less land area, and by using same or a less amount of water. As a consequence, it is important for the improvement of crop yields, and the sequestration of SOC in drylands, to correlate hydrological and C cycles by water conservation. Water conservation can enhance the low levels of SOC pools in dryland agriculture by using water-efficient agricultural systems and water harvesting. No-till farming system is an important option for the enhancement of SOC pools in dryland agriculture, which also proves a better option for drought management (Lal 2004b).

3.1.7 Soil C Sequestration and Global Warming

Global warming is a long term and universal problem. The C sequestration in soil is associated but separate issue, regardless from the debate of global warming, as it has its own intrinsic worth for the productivity enhancement, restoration of degraded soils and ecosystems, and water quality improvement. Several biophysical and societal benefits, can be achieved by compensating fossil fuels emission through possible SOC potentials. Moreover, soil C sequestration works like a bridge among three universal issues of climate change, biodiversity, and desertification.

3.1.8 Other Greenhouse Gases

The improvement in SOC pools enhances the ability of soil for the oxidation of CH_4, particularly in no-till farming systems (Six et al. 2002), however the N_2O emission can get worse (Smith et al. 2001b). The mitigation potential of CO_2 for soil management can be changed with fluxes of N_2O and CH_4, and should be well thought-out with respect to SOC sequestration.

3.2 Food Security

Globally, higher soil degradation, which needs restoration and soil C sequestration, is present in the areas such as South and Central Asia, Sub-Saharan Africa, China, the Caribbean, South American acid savannas and the Andean region. In South Asia and Africa, it is a norm to completely remove the residues for fuel and fodder purpose. As a result, stocks of SOC are depleted from the root zone, and productivity of soil and quality of environment in these regions have adversely affected. Poor farming community is more affected due to destructive practices, as they make use of marginal lands for cultivation with minimal inputs, produce poor yield, perpetuating to poor livelihood and lead to poverty. In the subsistence farming systems of Sub-Saharan Africa, the soil organic matter is the main source of nutrients for cultivated crops, as fertilizer consumption is only 2.5 %. This area represents 2 % of the global irrigated land area which is necessary for the C sequestration. Recommended practices cannot be predicted in rigorously degraded soils, due to depletion of their SOC pool which is the life support system of soils. The optimal SOC pool is required to (1) hold nutrients and water, (2) improve the structure of soil and tilth, (3) reduce the degradation and erosion hazards, and (4) deliver energy to soil microbes. The SOC pool acts as a bio-membrane which sieves the contaminants, degrades pollutants, declines hypoxia in the ecosystems of coastal regions, decreases sediment load from the rivers, as well as is a main sink for atmospheric greenhouse gases.

In Sub-Saharan Africa, application of fertilizer is a significant approach for the enhancement of crop yield (Pieri 1986), however its efficiency was improved by using in combination with mulching of trees (Sanchez 2002) and crop residues (Yamoah et al. 2002). Higher SOC pools results in more crop yields even in intensive agricultural systems (Bauer and Black 1994), particularly in soils with depleted SOC (Johnston 1986). The improvement in SOC up to one ton, enhanced the grain yield of wheat by 40 kg ha^{-1} in the semi-arid pampas of Argentina (Díaz-Zorita et al. 2002), and 27 kg ha^{-1} in North Dakota, United States (Bauer and Black 1994), 17 kg ha^{-1} of maize (*Zea mays* L.) in Thailand (Petchawee and Chaitep 1995), 3 kg ha^{-1} of maize and 6 kg ha^{-1} of wheat in alluvial soils of northern India (Kanchikerimath and Singh 2001) and 1 kg ha^{-1} of cowpea (*Vigna unguiculata* L.) and 10 kg ha^{-1} of maize in western Nigeria (Lal 1981). Better SOC pool is also required for sustainable yields by improved soil structure, nutrient and water holding capacity, and microbial activity. The critical level of SOC is 1.1 % for most of the soils in tropics (Aune and Lal 1997). In tropical ecosystems, an increase in SOC from a low level 0.1–0.2 % to the critical 1.1 %, is a major challenge. So far, a severe decline in SOC stock in Sub-Saharan Africa and somewhere else must be upturned to enhance food security. In Kenya, an 18-years study indicated that beans and maize yielded 1.4 t ha^{-1} year^{-1} without any input, and 6.0 t ha^{-1} year^{-1} when manure and fertilizer were applied as well as stover was retained, the consistent SOC pools were 23.6 t ha^{-1} and 28.7 t ha^{-1} up to 15 cm depth, respectively (Kapkiyai et al. 1999). This type of significant increase in the yields of crops is required at large scale to ensure food security.

In conclusion, balanced use of C based inputs is required to enhance the effectiveness, to reduce the C losses, as well as for improving food production and to make sure sustainable use of land and water resources. The erosion processes removed the SOC through the sediments, enriched with SOC, which either transferred to landscapes, settled down in depressions, or may passed to the water bodies. Thus an effective soil erosion control is required, to improve the environment quality, and sustainability of dryland soils. To improve the agronomic yields, and SOC sequestration in dryland soils, it is essential to correlate C and hydrological cycles by water conservation. A number of biophysical and societal benefits, can be achieved by pay off fossil fuels discharge through possible SOC potentials. Furthermore, SOC sequestration acts as a bridge between desertification, climate change, and biodiversity. Improved SOC pools are essential for sustainable productions through better soil structure, nutrients, water holding capacity, and microbial activity. This type of improvement is required at large scale to ensure food security.

4 Carbon Sequestration to Combat Land Degradation in Drylands

If the period of dryness continues for 1–2 years, the condition is considered as drought, a typical characteristics of drylands. So the leading character of drylands is water scarcity. Water shortage is a severe constraint for productivity, and hence affects the buildup of C pools in the soils. This issue becomes worse as the rainfall is not only below average but also unpredictable, that's why better management of available water is necessary in these areas. Additionally, temperature decreases the pools of SOC exponentially (Lal 2002a). As a result, dryland soils hold very less C stocks about <0.5–1 % (Lal 2002b). The depletion of SOC pools due to excessive land uses, can be overwhelmed by adding plant biomass into the soils (Polwson et al. 1998; Lal 2001). The degradation and desertification are prevailing in the dryland soils, which result in huge decline in SOC stocks. The increase in SOC stock improves soil quality, which have a significant impact on economic and social livelihood of the people in these regions. The factors responsible for C sequestration capacity in cultivated lands are climate, soil, vegetation cover as well as management skills. That's why C sequestration refers to the ability of lands and forests in agriculture sector to remove CO_2 from the atmosphere. Photosynthetic trees and crop plants absorb the CO_2 from the atmosphere and store as C biomass in leaves, branches, trunks, roots and soil. The largest sinks are the forests and grasslands, as they can store higher amounts of C in their leaves and roots for longer periods of time, however the terrestrial sinks are soils. Carbon holding capacity of organic matter present in soil is greatly influenced with C added from dead materials of plants and respiratory losses of C, decomposition, and both natural and anthropogenic activities with soils. Farmers can slow down the C losses from the soil by the adoption of good farming practices which include minimal soil disturbance and permanent soil cover. The biomass and soil C sequestration from the atmosphere, not only decreases the greenhouse effect, however, it also helps to keep up the restorative ability of soils for the sustainable production and environmental issues. Drylands are less prone to C losses than the wet soils (Glenn et al. 1992), because water scarcity restricts the mineralization in soil, and hence the C flux to the atmosphere. Thus in dryland soils, the C habitation period is more, occasionally extensive than the forest soils.

In conclusion, land degradation and desertification are widespread in drylands, and have caused substantial decline in SOC pools. The SOC, improved the soil quality, which have major influence on the economic and social livelihood of the societies. Climate, vegetation cover, soil, as well as management skills, are the elements of soil C sequestration ability in cultivated lands. Soil C sequestration and biomass accumulation from atmosphere, not only reduce the greenhouse effect, but also supports the invigorating capacity of the soils for the sustainable production and ecological aspects.

5 Management Options for Carbon Sequestration

The SOC concentration can be increased by enhancing plant growth with supplemental irrigation and good soil moisture regime, and the adaptation of better soil management practices. Water use efficiency (WUE) can be enhanced by reduction in losses due to surface runoff, evaporation by residue mulching which can also help in lowering soil temperature. The C pools in the soil can also be increased by adopting some strategies such as conservation tillage, water management, organic cultivation, better cropping systems and land use, and land restoration, these are also called advanced farming practices. Soil organic matter contents increased by organic farming systems, with the use of animal manures in composted form, and cover crops (Rodale 2003). The emissions elimination take place from manufacturing and transport of synthetic fertilizers, by adopting organic farming systems. The conservation and improvement of soil, water and air quality is possible through land restoration and land use changes, which usually reduces the emission of greenhouse gasses. Organic matter present in the soil is responsible for soil quality, it is a dynamic pool and responds effectively to changes in soil management, and primarily biomass production resulted from C inputs and tillage.

5.1 Conservation Tillage and Residue Management

Conservation tillage can improve the WUE, and plough till to no-till conservation strategy reduce the risks of soil degradation, improve the SOC concentration and soil quality over time. After the period of 24 years (1943–1966) of cultivation, 9.3 g kg^{-1} SOC was present in a plowed clean fallow treatment as compared to sweep-tilled late fallow, which was 118 g kg^{-1} SOC, in Bushland, Texas (Jones et al. 1997). The amount of SOC was measured after 8 years of no-till, up to 20 cm depth, and on the paired water sheds the treatments of stubble mulch were started for the cultivation of wheat-sorghum-fallow rotation (Unger 1991). For no-till, the average SOC concentration up to 10 cm depth was 16.3 and 15.8 g kg^{-1}, and treatment of stubble mulch indicates the trend for gain in SOC in no-till treatment (Stewart and Robinson 2000). In the upper 2 cm depth, the concentration of SOC significantly increased. The SOC was improved by 60 to more than 600 kg C ha^{-1} $year^{-1}$ due to one of pleasing consequences of no-till system (Stewart and Robinson 2000). On the soil surface the residues were left in winter cover crops, highest rates of SOC were associated with them. The continuous no-till wheat cropping system, during 10 years accumulated the C about 560 kg ha^{-1} $year^{-1}$ in northern Colorado (Potter et al. 1997). Under no-till with crop residue retention, the SOC in vertisols was observed in higher concentrations in Queensland, Australia (Dalal 1989). After 18 years of no-till practices in top 2.5–5.0 cm layers the significant improvement in SOC was observed (Dalal et al. 1995). The soil analysis from a 45-years old tillage system in India, showed that the SOC concentration improved by incorporation of biosolids (Kihani and More 1984). In West African Sahil, the annual addition of crop residues by 4 Mg (mega gram) ha^{-1} resulted in the similar SOC levels, maintaining in fallow in top 20 cm layer (Bationo et al. 2000). In southern Spain, in the traditional tillage system after 2 0years the SOC concentration was 0.84 % in 0–5-cm depth and 1.1 % in conservation tillage, and after 4 years in traditional tillage 0.89 % as compared to 1.34 % in conservation tillage system (Murillo et al. 1998). The soil quality was improved with the increase in concentration of SOC in dry land ecosystems, and sequestration of SOC can be enhanced by adapting no-till farming in wide range.

5.2 Rotations and Cover Crops

For enhancing the SOC concentration, use of conservation tillage gives beneficial effects, and accentuated in combination with suitable pastures rotations or cover crops (Ryan et al. 1997). The SOC concentration increased threefold, when wheat grown on sandy soil in rotation with alfalfa, as compared with sowing of continuous wheat in Saudi Arabia (Shahin et al. 1998). The soil quality was improved with silvo pastoral system and legume based rotations in Algeria (Arabi and Roose 1989; Roose 1996). In Syria, inclusion of Medicago in rotation, improved the SOC concentration (Ryan 1997). In Syria, in calcareous soils the SOC pools under different rotations were evaluated. Wheat-meadow rotation increased the SOC pool by 1.6 Mg ha^{-1} with an average rate of 0.17 Mg C ha^{-1} year^{-1} than wheat-wheat rotation, and wheat-fallow rotation 3.8 Mg ha^{-1} at an average rate of 0.38 Mg C ha^{-1} year^{-1} (Jenkinson et al. 1999). In Australia, the SOC concentration increased from 1.18 % to 1.37 % in 0–15 cm depth, where alfalfa and prairie grass were grown as pasture after 2–4 years (Whitehouse and Littler 1984). The rate of increase in concentration of SOC under Rhodes grass was 550 kg C ha^{-1} year^{-1} (Skjemstad et al. 1994), and under grass and legume pasture was 650 kg C ha^{-1} year^{-1} in a Vertisol (Dalal et al. 1995), the similar effects of pasture were also observed in New South Wales (Holford 1990; Chan 1997). The SOC concentrations were improved by continuous cultivation and manuring over 3 years up to 20–40 % in central India in a vertisol (Mathan et al. 1978). In rice-wheat cropping system, SOC concentration was increased with the incorporation of legumes in northern India (Singh et al. 1996). Deep and prolific root crops showed encouraging effects in subsoil on concentrations of SOC. Different rotations using annual crops (4 1/2 years) and mixed meadows (5 1/2 years), retained the stock of SOC at 17.3 Mg C ha^{-1}, as compared to 11.2 Mg C ha^{-1} in continuous cropping in wheat-sunflower rotations (Galantini and Rosell 1997).

5.3 Integrated Nutrient Management

The improvement of soil fertility, is essential to enhance the SOC concentrations in to the soil profile. High yields are obtaining with the nitrogen fertilizer application, however, it has little effects on the concentrations of SOC, unless it is used in combination with no-till and residual management (Skjemstad et al. 1994; Dalal et al. 1995). The SOC sequestration is limited in by using biomass C as input in semi-arid conditions. Whereas, the significant increase in crop yield with application of nitrogen, but for the balance of mineralization rate, the residue input is not sufficient. Fertilizers application with recommended rates resulted in significant increase in the concentrations of SOC in Syria (Ryan 1997). After 13 years of no-till, positive effects were observed on the concentrations of SOC, retained by nitrogen application and residues (35.8 Mg C ha^{-1} vs. 34.5 Mg C ha^{-1}) (Dalal 1989). In India, it was reported that the concentrations of SOC were improved using manure at 10 Mg ha^{-1} (Gupta and Venkateswarlu 1994). The concentrations of SOC improved by green manures, farmyard manures, biosolids, and compost applications. Significant increase in concentrations of SOC is possible with the use of high lignin amendments, and recalcitrant for breakdown.

5.4 Pasture and Rangeland Management

The surface residue management in a proper way, and conservation, can enhance the C sequestration with the adaption of improved grazing practices, as the major land use is grazing in the dry lands. In dry land ecosystems, the concentrations of SOC were improved with the advancement in pasture management, and by pasture conservation in the degraded lands (Conant et al. 2001). In degraded vertisols of semi-arid tropics of Australia, the SOC concentration was enhanced by pasture restoration with barrel medic (*Medicago truncatula* Gaertn.) and Mitchell grass (*Astrebla lappacea* F.Muell.), from 1.3 % to 1.6 % respectively, in 0–5 cm depth in the period of 4 years (Chan et al. 1997). Legumes incorporation improved the concentrations of SOC through biological nitrogen fixation process. Hence, the nitrogenous fertilizers application increased the concentrations of SOC in the degraded pastures. Pasture species grown better, however in addition to this perennial woody legume integrated in grazing systems to enhance the concentrations of SOC through the transfer of C to lower depths in sub-soils. In USA, the comparison of SOC pool was done for four sites on Pullman silty clay loam, first site was comprised of a >50 years dryland cultivated wheat, second was native to grassland, third site was a cropland rehabilitated to grassland before 37 years of sampling, and fourth site was a field return to a 7 year grassland before sampling procedure (Stewart and Robinson 2000). The results from these experiments showed significant addition in SOC concentration even under semi-arid environments. Controlled stocking and recommended burning rates are also essential for sustaining and successful accumulation of SOC.

In conclusion, the WUE can be increased by reducing runoff and evaporation losses, and organic mulching is important for optimal soil temperatures. The SOC pools can be improved by adapting conservation tillage, organic farming, better cropping systems, and land restoration. Conservation strategy like, no-till can reduce the risk of soil degradation, increase the SOC concentration, and soil quality over time. Conservation tillage, in combination with suitable pastures rotations or cover crops, can improve the WUE. The soil fertility enhancement, is crucial for SOC concentrations in soil profile, it can be improved by farmyard manures, green manures, biosolids, and compost applications. The major land use practice is grazing in drylands, the SOC concentrations can enhance by pasture management, and pasture conservation in degraded soils.

6 Conclusion

The above discussion supports the following conclusions: (1) the world drylands cover gigantic areas, with different land uses, and a wide range of soils and environments. (2) A severe problem of land degradation and desertification of drylands is prevalent, possibly caused by misuse of land, mismanagement of soil, and extreme climatic conditions. (3) Significant losses of SOC, from a total pool (241 Pg) caused by land degradation and desertification are estimated at 20–30 Pg, out of this, about two-thirds (12–20 Pg), can be re-sequestered by restoring desertified soils. (4) Food security can be achieved through soil C sequestration strategy as it improved the soil quality and health. (5) The average SOC sequestration potential is about 1 Pg C year^{-1}, with the adaptation of recommended practices on grazing lands and croplands, and by afforestation with Acacia, Mesquite, Neem etc.

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